THE UNIVERSITY OF ALBERTA

MAGNETIC FIELD PERTURBATIONS IN THE MAGNETOTAIL DURING MAGNETOSPHERIC SUBSTORMS

by

© FREDERICK PAUL CAMIDGE

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE

OF MASTER OF SCIENCE

DEPARTMENT OF PHYSICS

EDMONTON, ALBERTA

FALL, 1972

UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled MAGNETIC FIELD PERTURBATIONS IN THE MAGNETOTAIL DURING MAGNETOSPHERIC SUBSTORMS, submitted by Frederick Paul Camidge in partial fulfillment of the requirements for the degree of Master of Science.

ABSTRACT

Using data from the Imp A and Imp B satellites, it is shown that at the onset of an intensification of the magnetic perturbation field during the expansive phase of a polar magnetic substorm, there may be a pronounced effect in the magnetotail at the satellite location. This effect typically involves a reduction of tail field magnitude and a rotation of its direction about an axis lying approximately parallel to the solar magnetospheric Y direction. The distribution of these effects in the solar magnetospheric X direction is displayed and considerable discussion is presented on the interpretation of these data in the context of field line reconnection occurring in the magnetotail. Also, however, it is shown that the satellite may observe either no perceptible change in the tail field, or a magnetic field configuration which is becoming more tail-like. The latter implies an increasing level of magnetic energy stored in the tail and may be contrasted with the process of field line reconnection which reduces this energy level. It is suggested that the above results are consistent with a model involving reconnection in a localized volume within the tail and further, that such reconnection affords a mechanism for removing excess magnetic flux from the tail, thus creating the substorm.

ACKNOWLEDGEMENTS

The author wishes to express his gratitude to Dr. G. Rostoker for his supervision during this research, to Jerry L. Kisabeth for his fastidious reproduction of diagrams, and to Mrs. Gail Williams for the typing of this manuscript.

I am also indebted to the National Space Science Data Center of N.A.S.A. for supplying the satellite data, the Defence Research Establishment of the Pacific for permission to use their rapid-run micropulsation data, and to the World Data Center A for supplying the normal magnetograms.

This work was supported by the National Research Council of Canada. Also, I wish to thank the National Research Council of Canada for financial support received during this research.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

List of Illustrations (Continued)

List of Illustrations (Continued) Page

CHAPTER 1

INTRODUCTION

1.1 The Quiet or Average Magnetosphere

Chapman and Ferraro (1931) were the first to suggest that the magnetic field surrounding the Earth is not always well approximated at distances of several earth radii by that of an isolated dipole. They proposed that the highly ionized conducting gas emitted by the sun during a solar flare would, on reaching the vicinity of the Earth, cause its magnetic field to be confined within a cavity. Within this cavity, the field on the sunward or day side of the earth would be compressed, resulting in a higher field intensity than that of the undistorted dipole, while on the night side, the cavity would extend further from the Earth. This field within the cavity was predicted as the resultant vector sum of the approximately dipole field of the Earth, and that caused by the currents flowing in the cavity boundary. However, it is emphasised that these authors proposed this model to describe the Earth's magnetic environment during solar flares, and assumed that at other times an interplanetary vacuum existed and the dipole field was undistorted.

Biermann (1957) declared, on the basis of his studies of comet tails, that solar corpuscular radiation is always present, with a momentum flux great enough to ensure a minimum acceleration of the ions in the comet tails of twenty times that of solar gravity (the mean being about 100 and the maximum several thousand times solar gravity following flare conditions). Parker (1958) termed this radiation the "solar wind", and it

becomes apparent that its continual presence implies the associated continual existence of the cavity containing the geomagnetic field. This region, the magnetosphere, may be expected to vary in shape and size with solar wind conditions. In particular, its extent downstream from the Earth is inversely related to the degree of thermal motion of the solar wind particles. Johnson (1960) discussed this, and suggested that the magnetosphere would have a teardrop shape with a ratio of boundary distances for the day and night side of one to six, with a solar wind temperature of $10{,}000^{\circ}K$. Beard (1960), and Spreiter and Briggs (1962) have examined the shape of the upstream boundary of the magnetosphere in more detail. By equating the magnetic pressure just inside the boundary to the inwardly directed pressure on it, resulting from the elastic collision of the solar wind particles with the geomagnetic field, they have shown this boundary to have an approximately hemispherical shape.

The first experimental evidence of the form of the outer geomagnetic field came from the space probe Pioneer 1, launched in 1958 on an approximately 1 p.m. trajectory (i.e., in a meridional plane in which the local time is 1 p.m.). Sonnet et al. (1960) have shown, using data obtained in the intervals 3.7 - 7 Re and 12.3 - 14.8 Re, no measurable departure from the extrapolated dipole field values in the former region. In the latter region, wild fluctuations in the field were observed out to approximately 14 Re, beyond which the field magnitude dropped quite abruptly from the 15 - 35 γ range ($1\ \gamma = 10^{-5}$ gauss) to a relatively smooth value of about 5 γ. Two years later, Pioneer 5 confirmed these results, showing that the field fluctuations were present beyond 10 Re, and further, that in the

region 7 - 13 Re, a measurably greater ambient field than that predicted by an inverse cube law was to be found.

Following this, Heppner et al. (1963) observed that Explorer 10, on a 9 p.m. trajectory, experienced magnetic fields beyond 10 Re in a direction consistent with theories predicting the pulling of the geomagnetic field in the antisolar direction. At about 22 Re, the field dropped from 30 to about 10 γ, while fluctuations in direction simultaneously appeared. Detailed knowledge of large parts of the magnetospheric boundary and the field morphology both inside and outside were obtained by the earth-orbiting satellites, Explorers 12 and 14. This was possible because their active lives spanned many months, during which time their eccentric orbits precessed through large angles in a coordinate system fixed with respect to the magnetosphere. However, the results of these will not be discussed here as the Imp A satellite, launched in late 1963, confirms and extends the observations of these two vehicles, and furthermore provides most of the currently accepted knowledge of the quiet or average magnetosphere.

This satellite exhibited an orbit with apogee of 31.4 Re, perigee 192 km and an initial 9 a.m. direction of its major axis. For details of the results of this experiment the reader is referred to Ness et al. (1964), Ness (1965), and Figure 1 of this manuscript for a pictorial summary of the information that it, together with previous experiments, yielded. In its active life, the satellite major axis precessed to a 10 p.m. direction, measuring three vector components of the magnetic field with an accuracy of $\pm\frac{1}{4}\ \gamma$. First, the clarification it provided of previous experiments will be discussed.

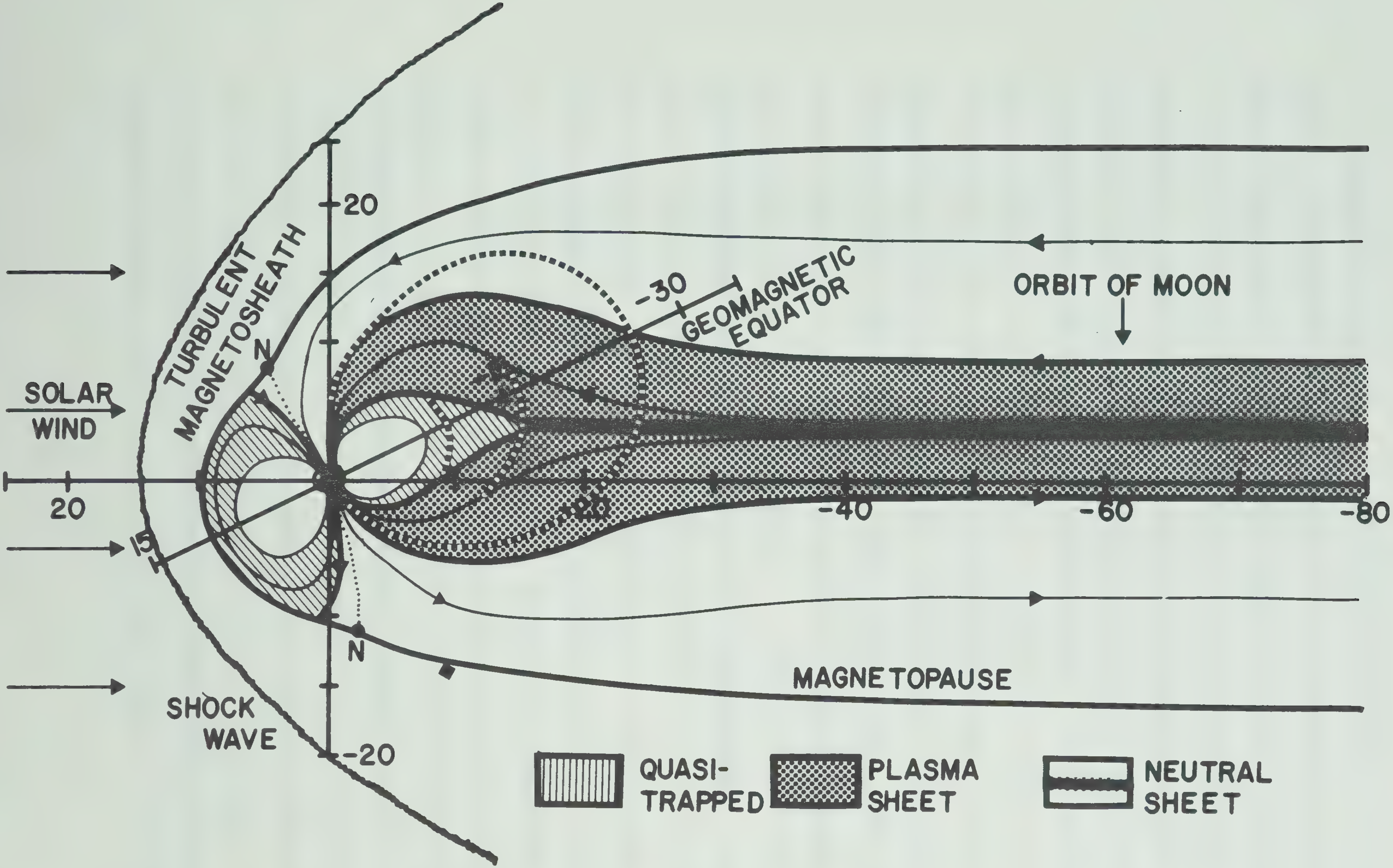


Figure 1

MAGNETOSPHERE AND TAIL

Consider the existence of a bow shock wave upstream from the magnetosphere. Examination of the velocities of the possible types of hydromagnetic and acoustic waves in the interplanetary plasma yields magnitudes less than the solar wind velocity. On this basis the shock was predicted by Axford (1962) and Kellogg (1962), and was subsequently observed by satellites at distances between 13.4 Re at the sub-solar point and about 20 Re on the Earth's magnetic axis. It is defined magnetically by fields typically of 4 - 7 γ magnitude with variances of less than 0.4 γ for extended times on the upstream side, and field magnitudes two or three times greater with wild fluctuations in magnitude and direction on the downstream side. This region of turbulence behind the shock in which the solar wind is thermalized is called the magnetosheath, and its general form is shown in Figure 1. The boundary between the magnetosheath and magnetosphere is called the magnetopause. Magnetically, this boundary is very clearly defined with the field magnitude increasing from 5 - 20 γ in the sheath to 30 - 60 γ in the magnetosphere, and the variance correspondingly decreasing by a factor of about four.

The clear delineation of the three regions, the magnetosphere, the magnetosheath and the interplanetary field by Imp A resolved many problems in the interpretation of earlier data. However, perhaps a greater contribution was made through the detailed knowledge gained of the magnetic field in the night side magnetosphere beyond 10 Re, as shown in Figure 1. In this region the magnetic field is well approximated by two slabs within which the field is parallel and anti-parallel to the anti-solar direction to the south and north respectively of a narrow transition region. This region, about 600 km thick, is called the

neutral sheet because of the low field values found there. In order to support these slabs of field, termed the magnetotail, plasma must be present in and around the neutral sheet, essentially because the large value of curl B requires a crosstail current. This was predicted by Axford et al. (1965). The search for a knowledge of particle distributions within the magnetosphere has paralleled that of the magnetic field. Only those leading to the discovery of the plasma sheet will be discussed here.

Freeman (1964) discussed particle data from Explorer 12, which exhibited a significant dayside-nightside asymmetry in the energetic electron (>50 kev) distribution with termination of this distribution some 2 Re closer on the night side. Perhaps more important for our purposes, was an intense flux of electrons in the 1 - 10 kev range found on the night side beyond the Van Allen radiation belts out to the satellite apogee at 14 Re. Later Anderson (1965), using data from Imp A, observed sudden appearances in the tail of electrons with energies greater than 45 kev. Although he claimed the existence of a dependence of the frequency of these events on radial distance from the Earth and magnetic latitude, Murayama (1966), in a more detailed analysis, declared the former to be entirely spurious, and further, that a clear inverse dependence on the distance from the neutral sheet was present. Also, Anderson and Ness (1966) have shown that, of the reductions of magnetic field usually associated with the appearance of these electrons, only one per cent can be accounted for by their diamagnetic effect at the observed densities. This implies that if diamagnetism is the cause, then probably other particles of a different energy range are also present.

The existence of the plasma sheet within the range 16 - 18 Re from the Earth was first tangibly demonstrated by Bame et al. (1966) when they observed the electron component of this particle distribution. This was achieved on the Vela-2 satellites with simultaneous measurements of low energy electrons ($0.35 \leq E \leq 20$ kev) and energetic electrons ($E > 45$ kev). The latter, it was remarked, were the high energy tails of the distribution, and were subject to considerable changes in count rate through the rather common occurrence of impulsive energisation of the permanent electron population, as shown by the lower energy data. We know now, largely from the evidence accumulated from the Vela satellite program, that the plasma sheet contains electrons of average energies of 1 - 7 kev with densities of 0.1 - 0.3 particles/cm^3, and protons of energies 1 - 10 kev. Also, the thickness varies from 4 - 6 Re in the noon-midnight meridional plane to approximately twice this in the wings of the magnetosphere.

It should be noted that Figure 1 represents an incomplete picture of the magnetosphere. This occurs because the length of the tail is not experimentally resolved. Study of the tail at large distances is made difficult by the fact that the expected field magnitudes decrease to that of the interplanetary medium and further, it is speculated that the tail may break up into filaments containing bundles of field lines. However, clear tail field was observed intermittently by Pioneer 7 at distances of 1000 Re.

1.2 The Interaction of the Interplanetary Medium with the Magnetosphere

Predictably, while experimental information on the form of the mag-

netosphere and surrounding regions was being accumulated, various theoretical models were postulated. Dungey (1961) suggested that the magnetospheric field may have a dynamic interaction with the interplanetary field.

When two slabs of anti-parallel field are in close proximity, as in Figure 2 in the X direction, it has been suggested by Sweet (1958) and others that the lines close to the transition region will merge, causing a "reconnection" of these lines, creating different lines which will move out of the reconnection region. The new lines will, near this region, have a large component in the Z direction. The direction of flow of these lines in and out of the reconnection region is shown in Figure 2 by the heavy arrows. The point in the centre of the pattern is sometimes referred to as an X-type neutral point.

While usually the interplanetary field lies approximately parallel to the ecliptic plane, it may have a component perpendicular to this plane. Dungey postulated that during periods when a southward component was present, field line merging with the oppositely directed geomagnetic field on the sunward side of the magnetosphere may occur. As shown in Figure 3, the newly formed field lines then sweep over the poles until they reach a configuration where they lie approximately parallel and anti-parallel to the anti-solar direction forming the magnetotail. According to the model, merging again takes place, this time in the tail, and the field lines which were temporarily connected to the interplanetary field become again solely connected to the Earth. To complete the flow pattern, the field lines must contract and move round the Earth to the day side again, where they then expand to fill the

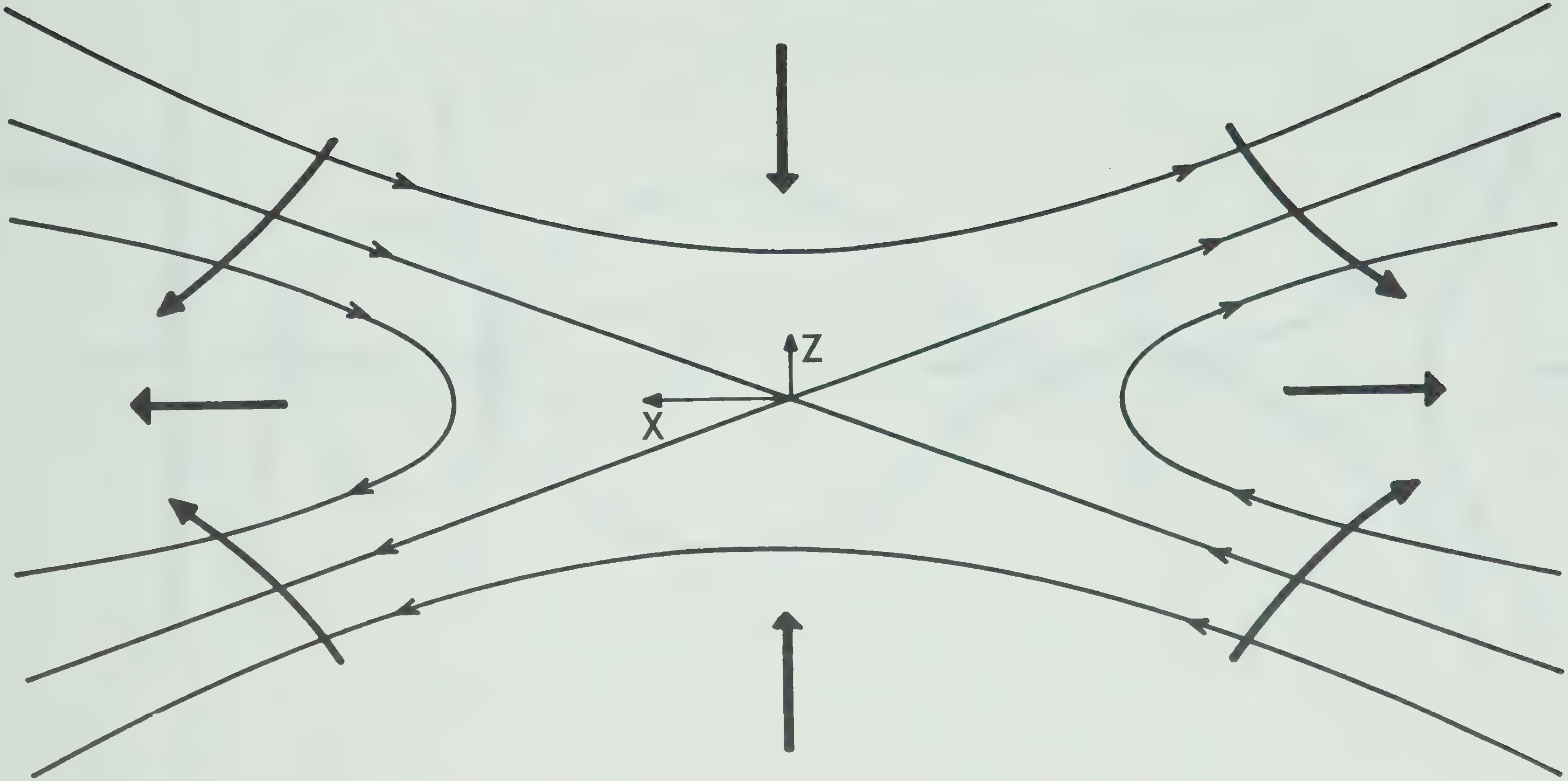


Figure 2

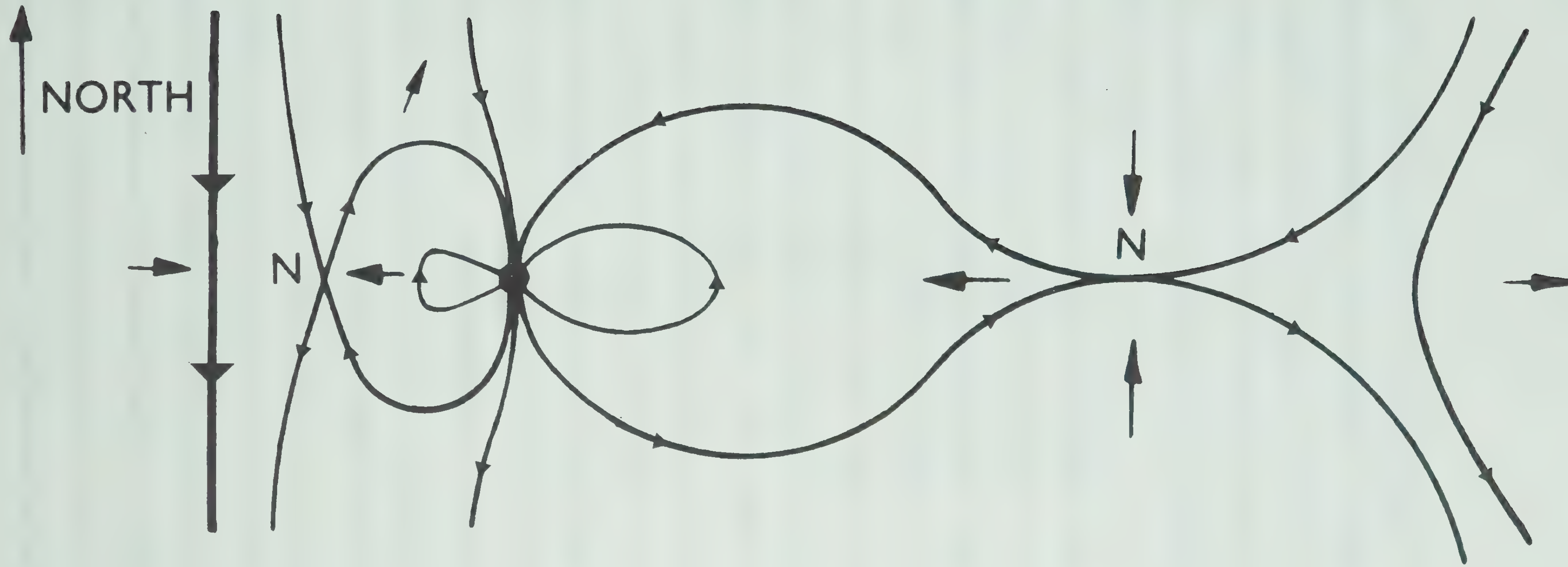


Figure 3

space left by other lines merging with the interplanetary field, and possibly merge again themselves. The concepts involved in this model in a modified form are central to the work presented later in this thesis. It should be noted that the merging pattern in Figure 3 does not show the extended tail reflecting the uncertain knowledge of the tail shape at this time.

Piddington (1960) proposed that at the magnetopause boundary a frictional effect occurred, causing the solar wind to drag field lines from the sunward side to the night side where they would create an extended geomagnetic tail. He considered (Piddington, 1962) a flow pattern in which the outer geomagnetic field lines are caused to move around the Earth on the dusk and dawn side with the solar wind as a result of this frictional drag. These lines eventually enter the tail and contract towards the Earth whereupon they flow around the Earth at lower altitudes in the reverse of their previous direction. On reaching the sunward side, they may expand and repeat the process. This is essentially the model examined earlier in considerable detail by Axford and Hines (1961). They attempted to analyse the effect on the flow pattern of a rotating Earth and also the motion of energetic magnetospheric ionization. It should be noted that in contrast to Dungey's model the field lines remain closed at all times.

Dessler (1964) has examined factors which determine the length of the tail. His analysis is based on the condition that the sum of the geomagnetic field pressure, the plasma pressure and the hydromagnetic wave radiation pressure within the tail balance the field and plasma pressure outside the magnetosphere. Hydromagnetic waves in the day-

side magnetosphere may be generated by sudden changes in solar wind pressure. These propagate into the tail, and it is argued that these alone provide enough pressure to maintain an open tail to distances of 20 - 50 A.U. Though this has been subsequently criticised, his argument for a minimum tail length of a 100 Re seems quite reasonable. With no internal pressure whatsoever, the solar wind can only close the tail at a maximum rate defined roughly by the magnetoacoustic velocity, Vm, which he estimates to be about 70 km/sec with a solar wind temperature of 10^5 ^oK, proton number density of $5/cm^3$ and a magnetic field strength of 5 γ. If Vs is the solar wind velocity and b the largest transverse magnetospheric radius, and Vs and b are taken to be 500 km/sec and 15 Re respectively, then the minimum tail length is of the order $(Vs/Vm)\ b \cong 100$ Re.

Axford et al. (1965) discussed field line merging in detail, particularly with regard to the formation of the long tail, the existence of which had then been indicated by the data of Explorers 12 and 14. Their model involved a tail with two anti-parallel field slabs in which merging takes place through a crosstail line in the neutral sheet several tens of earth radii from the Earth. They further pointed out the currents which must flow in the magnetopause and neutral sheet to satisfy the field conditions. This paper will be mentioned again in discussing the magnetic disturbances present in the magnetosphere.

Dessler (1968) examined the crosstail current densities required to maintain the tail field observed and concluded that merging was most likely to occur within a distance of 30 Re from the Earth. This follows because the observed particle densities in the plasma sheet in this range

are at times inadequate to support the currents necessary to sustain the large tail field values found there compared with those at greater distances. For a more detailed analysis of this suggestion the reader is referred to Hill and Dessler (1971).

1.3 Time Varying Aspects of the Magnetosphere

If one observes the conditions in the Earth's upper atmosphere and above, particularly in the night-time regions, one finds evidence of significant temporal changes in the particle populations and magnetic field values. In order to study such variations, it is useful to search for disturbances whose signatures have a statistically significant pattern. Magnetospheric substorms represent such disturbances and their frequency of occurrence is large enough to provide a statistically significant sample size over relatively short periods of time (e.g., several weeks). Typically they last for 1 - 3 hours and may occur as isolated events, or in a succession lasting many hours resulting in a geomagnetic storm. A magnetospheric substorm is comprised of a polar magnetic substorm, a micropulsation substorm and others describing the particle deposition in the atmosphere, the visual aurora, X-rays produced, etc.

The polar magnetic substorm describes the variation of the three components of the magnetic field on the Earth's surface during a magnetospheric substorm, and is caused by current systems in and above the ionosphere. The micropulsation substorm describes high frequency periodic oscillations superimposed on the long period variations during the substorm, probably due to the existence of hydromagnetic waves in

the magnetosphere. These two are mentioned in particular because of their relevance to the work described later. Within the micropulsation substorm, those oscillations in the period range 40 - 150 sec which are "impulsive", i.e., of limited duration, are labelled Pi2, and are of special interest because they always accompany the polar magnetic substorm and are often seen over a large part of the night side hemisphere. Furthermore, unlike the polar magnetic substorm, they have a distinct and synchronous onset over the area in which they are seen which is coincident with the polar magnetic substorm onset close to the current system causing it.

Currently, the temporal development of a magnetospheric substorm is thought to consist of three distinct phases. Although it has not at the present been exhaustively studied, there appears to be a period of gradual intensification of activity prior to the subsequent explosive increase in the level of activity. The former has been labeled the <u>growth phase</u> by McPherron (1970) and appears to be associated with the injection of energy into the night side magnetosphere. The ensuing explosion of activity represents the <u>expansive phase</u> and accompanies the northward motion of the previously undisturbed auroral arc structures. Finally, the return of these arcs equatorward and the associated decrease in level of activity is called the <u>decay phase</u>.

The term "level of activity" used above describes the behaviour of the magnetospheric substorm in total and refers to the sum of the various types of activity within the substorm (i.e., polar magnetic, micropulsation, X-ray, etc.). The polar magnetic substorms in the growth phase display a gradual departure from the base line of some

or all of the magnetic field components over a period of anywhere from zero to two hours. The sign of this perturbation is governed by the locality of the observation with respect to the substorm current system. The expansive phase is represented by much larger and more rapid perturbations, and the decay phase by a return of the components to their quiet time values. The Pi2 micropulsations occur in bursts during the expansive phase, the first burst being synchronous with its onset. It is this onset which is later referred to as the "substorm onset". For discussion of behavior of other types of substorms with respect to this onset, the reader is referred to Akasofu (1968).

Recently, evidence has been gathered which suggests that a distinct and repeated substructure exists within the substorm. Rostoker (1968) observed that most substorms are accompanied by at least two distinct Pi2 bursts, separated by 10 - 30 minutes. For most of these it was found that the first was associated with a small spatially well localised magnetic disturbance, and the second with a major disturbance. These were termed the trigger bay and main bay respectively. It was assumed that in cases where the trigger bay could not be found, it had occurred but in a spatial region not observable from the available data. In cases where several disturbances occurred, it was thought that they represented a sequence of the above pairs of trigger and main bays, each pair with its associated substorm.

However, Kisabeth and Rostoker (1971) have presented evidence indicating that the polar magnetic substorm, caused largely by an overhead westward flowing current, has the following time development. At the onset of the substorm the current at the southern border begins to grow.

It attains a value which it maintains fairly steadily during the substorm, while at the northern border a number of periodic intensifications of the current at roughly 15 - 20 minute intervals occur, implying an injection of energy with the same periodicity. Also a series of more than two Pi2 bursts may be associated with one substorm.

The early theories of substorm generation were not developed to describe the substorm phenomenon per se. However, the models of Dungey, Piddington, Axford and Hines, and Axford et al. mentioned earlier, discussed magnetospheric dynamics with partial reference to specific manifestations of upper atmospheric disturbances. These authors have based their theories on magnetospheric convection using various flow patterns. Here only the development of the field line reconnection model will be discussed further.

Two conceptually distinct processes may be involved in this merging. First, field lines may reconnect while diffusing through a stationary plasma, as a result of the finite conductivity, resulting only in a heating of the plasma from the currents present. This was the model treated by Sweet. Alternatively, assuming infinite conductivity, the plasma will be constrained to flow with the reconnecting field, producing bulk motion of the plasma. The energy of this motion may be partly converted into thermal motion if the plasma is compressed downstream from the reconnection region.

Petscheck (1964) has examined the mechanism of reconnection and concludes that away from the merging line, the plasma will be frozen into the field lines and will leave the merging region at velocities

up to a maximum given by the Alfvén velocity (depending on the extent to which the flow is controlled by conditions in distant regions). The flow rate into the merging region is likewise less than or equal to a maximum of one tenth of the Alfvén velocity. Only in the immediate vicinity of the merging region will significant diffusion of the field through the plasma occur. This occurs because the finite conductivity produces significant deviations in the currents from those required to sustain the high values of curl $\underline{B}$ in this region consistent with pure frozen field conditions.

Yeh and Axford (1970) have attempted a more detailed analysis of the fluid and magnetic field motion for the special case of steady incompressible inviscid hydromagnetic flow in two dimensions. They concluded that, in general, if circumstances controlling the overall flow at a distance from an X-type neutral point are favourable, merging may take place rapidly with frozen field conditions occurring everywhere other than close to the neutral point.

Axford et al. (1965) used the maximum merging rate derived by Petscheck to estimate the rate of energy flow Q in the magnetotail during reconnection. They assigned typical values to the tail width L, field strength B, particle number density p, and neutral sheet thickness w, of 2×10^{10} cm, 10 γ, $1/cm^3$ and 1 Re respectively. With these they obtained a value for Q of 4×10^{17} ergs using the formula $Q = (3B^2/8\pi)(B/\sqrt{4\pi p})\ L\ w$. Obviously such an estimate can be changed significantly by taking other, equally reasonable, values of the parameters involved. However, Axford (1964) and O'Brien (1964) obtain values of 10^{17} and 4×10^{17} ergs/sec respectively as estimates of the

rate of dissipation of energy in the aurora. Thus, this estimate of energy flow rate shows that field line merging could provide the necessary energy.

A significant modification of this model was suggested by Atkinson (1966). He proposed that reconnection in the tail occurs sporadically and implosively in response to conditions in the tail resulting in magnetospheric substorms, and between such times no merging occurs. This contrasts with previous concepts which usually involved a continuous process of merging enhanced during geomagnetic storms as a result of changing solar wind conditions.

Atkinson's model implies quasi stable magnetic field and particle populations in the tail which are gradually changed by transport of magnetic flux and plasma into the tail, either by merging at the sunward boundary, or convection round the wings. Eventually, subject to some triggering process, the energy resident in this configuration is unstably released through merging in the tail. This continues until the stresses in the tail have been relaxed at which time the process may be repeated as long as solar wind conditions are such as to cause the tail energy build-up. It is emphasized, however, that the solar wind conditions only indirectly affect the magnetospheric substorm process through their influence on the tail conditions.

Though the cause of the triggering of implosive reconnection was not discussed, it seems likely that two types of processes may occur in the reconnection region just prior to merging: (1) A high pressure wave front may be propagated into the region from the direction in which the plasma will flow into this region upon onset of merging;

or, (2) A low pressure wave front may propagate in from the direction in which the plasma will leave the region. Axford (1969) speculated on the latter possibility, suggesting that a rarefaction wave propagating back into the magnetotail may result from an ejection of the particles in the cusp region into the ionosphere.

In discussing the observations of the magnetosphere and surrounding regions in conjunction with the substorm, it is perhaps worth remarking on the evidence supporting the merging theory on the sunward boundary. Fairfield and Cahill (1966) have shown that when the interplanetary field has a southerly component, there tends to be an associated geomagnetic disturbance at ground level, and that a northerly component is generally associated with quiet conditions. Further studies by Fairfield (1967) and Rostoker and Fälthammar (1967) have given support to these results. More recently, Aubry et al. (1971) have presented evidence of an inward motion of the magnetopause preceding substorms which is probably related to front side reconnection of magnetic field lines.

Data obtained within the tail gives currently a far from complete description of the processes occurring there. However, certain distinct effects are well established. Behannon and Ness (1966) using data from Imp A have shown that during a geomagnetic storm, the scalar magnitude of the tail field may be increased from 15 - 20 γ to 35 - 45 γ. Further, they examined the field increase in the early part of a storm when the satellite, approximately at apogee and 16.8 Re from the sun-earth line, was continually within the cavity. From this, assuming a previous tail radius of 20 - 22 Re, based on earlier quiet time observations, they

deduced that the maximum possible decrease of the tail radius (~3 - 5 Re) could not alone account for the increase in field strength from 15 to 35 - 40 γ. It follows then, if the above assumptions are correct, that extra flux must have been added to the tail, probably from the sunward side of the magnetosphere.

Heppner et al. (1967), using OGO A magnetometer results, observed a change ΔB in the magnitude of the field approximately fifteen minutes after the substorm onset as observed at the Earth's surface, provided the satellite is in approximately the same meridional plane as the ground based observatory. They found that $\Delta B > 0$ in regions where the measured field is less than that of the extrapolated dipole field, and $\Delta B < 0$ where the field is greater than the dipole field. This would be consistent with the merging theories because any reduction in the tail energy results in a reduction of the currents which are responsible for the tail field.

Rostoker (1968) in his discussion of trigger and main bays, points out that for at least one of Heppner's examples the field effect at the satellite occurring fifteen minutes after the onset of the trigger bay actually coincides with the main bay. He suggests that it may be possible to show that this is always the case given enough data to define the onsets of each bay.

Hones et al. (1967) observed that during the expansive phase of a substorm (defined by normal magnetogram traces) the plasma density on the Vela-2 satellites may drop below the detection threshold and reappear during the early part of the recovery phase if the satellite is suitably positioned with respect to the plasma sheet. Though troubled

(as indeed is typically the case in such studies) with the difficulty of determining substorm onsets accurately, because of inadequate data coverage on the Earth's surface, his current evidence (Hones, 1971), based on examination of a larger sample of data, suggests the following. During the growth phase there is a gradual reduction of the plasma density, followed by a rapid reduction at the onset of the expansive phase, and finally reappearance of plasma in the recovery phase. These findings will be discussed in more detail later.

However, one interpretation of this information is that during the growth and expansive phases of the substorm, plasma is drained out of the plasma sheet moving earthwards at an increasing rate, causing a reduction in its thickness. Later, at the onset of the recovery phase, the deposition rate of plasma into the upper atmosphere begins to decrease. Reconnection in the tail occurring with the plasma motion may cease simultaneously or some short time later. In either case, reconnected field lines may be expected to continue for some time to relax towards a more dipole-like configuration. Therefore, while taking on a greater extent perpendicular to the neutral sheet, they will under frozen field conditions allow a thickening of the plasma sheet.

To this time no direct evidence of merging has been presented. In order to do this it is desirable to clarify what direct manifestation such merging might have. Clearly, a rotation of field direction is involved, and on the earthward side of the reconnection region a much increased value of the field component northwards across the neutral sheet is created. Of course, this would also occur if only previously <u>connected</u> lines were to contract earthwards. However, when reconnection

occurs, a component of the magnetic field perpendicular to the neutral sheet and directed southwards is created on the anti-sunward side of the reconnection region. It is difficult to imagine any other mechanism which could achieve this and this feature should be acceptable as direct evidence of field line merging.

At the time of the work to be discussed in the main body of this thesis, the only direct evidence of merging had been presented by Mihalov et al. (1968). They studied magnetic field data collected by Explorer 33, which scanned to a radial distance of 82 Re in the neutral sheet. It was found that outside of 35 Re, a significant proportion of the neutral sheet crossings showed distinct southward normal components of field. For example, in orbit 1 of 127 samples, 17 per cent showed southward field. From September 6 - 10 in orbit 5, 33 per cent showed this effect. Only one example was found within 35 Re. The implication of this in terms of the reconnection theory is obvious. Furthermore, the observations suggest that southward field occurs intermittently thus favouring impulsive rather than continuous merging.

Laird (1969) examined the structure of the neutral sheet in an analysis of data gathered by Explorer 14. He discussed one example of a large southward field in the neutral sheet, and showed that this occurred during a period of substorm activity as observed at the Earth's surface. However, no accurate temporal relationship between the satellite and ground based observations was established.

It is apparent that in 1969, when the work discussed in the next chapter was initiated, there was some indication that field line reconnection may occur in the magnetotail. However, with the exception of

the one example presented by Laird (1969), no attempt had been made to relate this to the substorm phenomenon. Clearly there existed a need to establish whether or not such reconnection occurs, and if so what role, if any, it plays in the substorm process. The investigation described in the following pages attempts to make some contribution in this area.

CHAPTER 2

MAGNETOTAIL BEHAVIOUR OBSERVED DURING SUBSTORMS

2.1 The Data Sources

The object of this research was an examination of the behaviour of the tail magnetic field during the progress of a polar magnetic substorm. Data on the magnetotail field were obtained from the Imp A and Imp B satellites.

As mentioned in the previous chapter, Imp A was capable of measurement of three vector components of the magnetic field to within an accuracy of $\frac{1}{4}\ \gamma$. This was achieved with two monoaxial mutually perpendicular fluxgate magnetometers with a dynamic range of $\pm 40\ \gamma$. In a spin-stabilised craft, this gives tri-directional information. The spacecraft also carried a rubidium 87 vapor magnetometer whose accurate function requires temperature control within narrow limits. Care taken to ensure this resulted in temperature control well within the acceptable range of the relatively insensitive fluxgates. Clearly, only well-known preferably small spacecraft fields are permissible in order to utilise this instrument accuracy. Wherever possible, systems within the vehicle were made of non-magnetic or minimally magnetic materials. As electrical circuits may carry currents which are variable, and not easily known during its operation, great effort was expended in spatially distributing these circuits so as to cancel all fields produced. The magnetometer sensors were placed 82 inches from the body of the craft. In addition, extensive preflight tests simulating launch and operational conditions were made to establish limits of confidence

on the magnetic field values measured.

The orbital characteristics discussed earlier allowed almost continuous observation of the tail field in the range 12 - 31.4 Re during the period of time for which data were available (approximately 2½ months). In its highly eccentric orbit, the satellite spent only a small proportion of each orbital period within 12 Re. Further details on the instrumentation and orbit can be obtained from Ness et al. (1964).

Due to a malfunction in the third stage of the launch vehicle, the satellite Imp B achieved less than half its intended apogee and a lower spin rate. Its actual initial orbital characteristics included an apogee of 15.9 Re, perigee of 197 km and major axis in the sunward direction. Its instrumentation for magnetic field measurements is identical to that of Imp A, and instrument accuracy may be assumed identical. When the field fluctuates significantly during one spacecraft revolution, the reliable accuracy of the fields obtained by spinning magnetometers is reduced. This occurs because effectively two magnetic field components are obtained by one magnetometer whose sampling direction is changing through rotation. Therefore, these two components are not recorded simultaneously and rapid temporal changes may result in spurious field magnitudes and directions. Thus, for fluctuating fields the accuracy is not as high as anticipated owing to the lower spin rate. However, the error so produced would not be consistent from one spacecraft revolution to the next, and therefore the 12 data point averages used in this study are not sensitive to this. It follows that the overall accuracy of the Imp B data may be assumed to be the same as for Imp A.

Clearly, with its lower apogee, Imp B spent a smaller proportion of

its time beyond 12 Re. However, useful data were obtained in the 12 - 15.9 Re range within which of course it experienced lower velocities than Imp A, resulting in greater confidence that field variations observed are temporal rather than spatial. The total data coverage of the two satellites extended over approximately 3½ months. Further details of the experiment may be acquired from Fairfield and Ness (1967).

The satellite data used were in the form of 5.46 minute averages of 12 data points of each of the three components of the magnetic field in the solar ecliptic co-ordinate system. Although the solar magnetospheric co-ordinate system is a more natural choice, the data were not made available in this form. This, however, was not considered a problem. The solar magnetospheric co-ordinate system has its X axis common with the solar ecliptic system and it rotates about this axis in a manner defined by the condition that its XZ plane always contains the Earth's magnetic dipole. This results in a rocking motion of the solar magnetospheric system in the solar ecliptic system with a complex harmonic motion comprised of two simple harmonic motions with periods of one year and one day. These result from respectively the Earth's orbital motion round the sun with its dipole inclined at 23^{o} to the solar ecliptic Z axis and the angle of eleven degrees between the Earth's magnetic axis and its rotation axis.

Clearly, the effect of transforming from one of these systems to the other results only in a redistribution of field in the Y and Z components. In the period of interest here, that is between the March equinox and summer solstice, we are particularly interested in changes in the Z component of the field. Examination of the relative positions of the two

co-ordinate systems shows that during this period, concurrent increases in the Y and Z components in the solar ecliptic system both contribute to increases in the solar magnetospheric Z component. It follows then that the reverse is also true. If, in cases where the perturbations in the Y and Z components have a different sign, the value of $-\Delta By \geq \Delta Bz.\text{cotan}\ (34^{o})$, this may indicate that the Z component perturbation is not only significantly different in magnitude, but possibly of different sign. This follows because 34^{o} is the maximum angle of rotation between the two co-ordinate systems. Thus, if $-\Delta By < \Delta Bz.\text{cotan}\ (34^{o})$, it can never destroy the Z component in transforming from solar ecliptic to solar magnetospheric co-ordinates. This consideration was kept in mind when examining the field variations at the satellite. In practice, however, $|\Delta By|$ is rarely larger than $|\Delta Bz|$ and the problem does not arise.

The neutral sheet position in the solar magnetospheric co-ordinate system was calculated using the work of Russell and Brody (1967). Using data from Imp A and OGO 1, they obtained the positions of twenty-one neutral sheet crossings. The surface which they considered represented the neutral sheet within the accuracy of their crossing position co-ordinates was defined as follows. All points in the neutral sheet with Y co-ordinates greater than or equal to 11 Re were in the solar magnetospheric XY plane. Those with smaller Y co-ordinates lay on a surface symmetrical about the sun-earth line, which contained a circle of radius 11 Re lying in the geomagnetic equatorial plane with its centre at the centre of the Earth. The position of the satellite was established in a co-ordinate system (Xsm, Ysm, Z) with axes parallel to those of the

solar magnetospheric co-ordinate system but located in space by the requirements that the Z axis be that of the solar magnetospheric system, and the XY plane contains a line in the neutral sheet parallel to the X axis having the same displacement in the Y direction as the satellite.

The geomagnetic data in the form of normal magnetograms recording three components of the magnetic field were employed to establish the existence of substorms throughout the period of available satellite data. These magnetograms were recorded at the stations listed in Table I(a). The characteristic form of the magnetogram traces which define the polar magnetic substorm are discussed in Akasofu (1968). Rapid run induction magnetograms from those stations in Table I(b) were then used to observe the Pi2 micropulsations associated with the substorm. The response of induction coil magnetometers varies strongly with the frequency of the recorded variations. Thus, the response is not flat over the Pi2 frequency band. In addition, while discriminating in favour of high frequency field variations, Pi2's (period 40 - 150 sec) are not distinctly isolated from accompanying micropulsation activity in nearby frequency ranges. Therefore, although identifying the first Pi2 burst onset is usually straightforward, the onsets of the second and subsequent bursts within the substorm if present are sometimes difficult to obtain, particularly the later ones as they are often immersed in Pil (period 1 - 40 sec) and other continuous high frequency micropulsation activity.

2.2 Treatment of Data

The method of analysis was as follows. The normal magnetograms

TABLE I

	Station	Geomagnetic Latitude	Geomagnetic Longitude
(a)	College	64.6 N	256.5 E
	Victoria	53.9 N	292.6 E
	Fort Churchill	68.6 N	322.6 E
	Agincourt	57.2 N	350.1 E
	Reykjavik	66.6 N	71.2 E
	Byrd	70.6 S	336.0 E
(b)	Great Whale	66.6 N	347.4 E
	Ralston	58.4 N	306.3 E
	Byrd	70.6 S	336.0 E

were first examined and the approximate onset times of all distinct substorms were obtained. The rapid run magnetograms were then used to determine the onset times of all distinct Pi2 bursts within the substorm. For the large majority of cases, only one or two onsets could be obtained within the acceptable accuracy of ± one minute. If an accurate Pi2 onset could be determined, i.e., it was not immersed in other activity or associated with a distant current system, the uncertainty is typically within ± one minute. Otherwise it is typically much larger (~ ±5 min). Those events for which Pi2 onset times could not be accurately determined were temporarily set aside. The satellite magnetic field data around these onset times were then examined for a corresponding effect in the magnetotail. The additional uncertainty in the time of the perturbation of interest within the 5.46 minute averages of the satellite data results in a total uncertainty of approximately ± six minutes.

In the second approach, the satellite data were examined for all decreases in the Bx component of magnetic field greater than 5 γ. In most cases these changes were between successive 5.46 minute data points. If this was not the case, the ensuing development of the event was studied to ascertain that the perturbation was indeed localized in time and not part of a long-term drift. If this condition was in doubt, the event was discarded. The normal magnetograms were then examined at the times of these perturbations and all those distinctly associated with <u>substorm</u> onsets were noted.

This second approach may appear redundant. However, the object of the first method was to examine the magnetic field correlation on an

individual substorm basis with emphasis being placed on the Pi2 onset times. In the second method, the condition of precise onset times from the Pi2 bursts was relaxed and only a single less accurate onset time for the substorm as a whole was obtained, allowing more events to qualify. These events were then used to examine statistically the magnetic field perturbations as a function of satellite position. A total of 138 events were observed where there was correlation between the magnetic field at the satellite and the onset of a substorm at the Earth's surface.

In other cases the tail field behaviour was such that no clear relation existed between it and the substorm manifestation on the Earth. Also, for some substorm events no response above the noise level was seen in the tail.

2.3 Results

Brief examination of the data revealed no predictable tail behaviour at the satellite during the substorms. However, on many occasions there was a response clearly related to the substorm. Despite its variability the behaviour observed may be comprehensively summarised as follows:

(1) At the satellite location, there may be concurrent with earth-bound substorm activity either no apparent change in the tail field, or, occasionally, the field may be becoming more "tail-like".

(2) Alternatively, coincident with the onset of a substorm to within an accuracy of ± six minutes, when only one Pi2 burst is observed, one may observe the following effects at the satellite:

(a) A sharp decrease in the magnitude of the tail field B.

(b) Such a decrease in B is found to be primarily contained in the variation of the X component of the tail Bx; that is, there is a sharp decrease in $|Bx|$.

(c) With the decrease in B, the Z component experiences a sharp perturbation of roughly the same duration as the effects in Bx and B. ΔBz may be negative (field increase southward) or positive (field increase northward).

(3) If there are two or more distinct Pi2 onsets, the observations in 2(a), 2(b), and 2(c) above may occur with the second and subsequent onsets. Clear examples of this are too few to determine any pattern in the effects at the satellite with these later Pi2 bursts. However, as will be shown later, these effects have been observed at the time of the second burst when two occur and also at the times of the second and third bursts when three occur. Also, some indication is present that effects such as those described above can occur late in the substorm, although it could not be shown to be synchronous with a Pi2 onset.

In no instance, when more than one Pi2 onset was identified, was there a tail effect with the first onset.

(4) Finally, temporal changes in the magnetic field at the satellite may occur having no simple relationship to the substorm as observed on the Earth's surface. Although this occurs frequently, because of the clarity and precision with which the effects in (2) above may be observed, it is considered highly improbable that their form and apparent association with the substorm is fortuitous. Rather, it

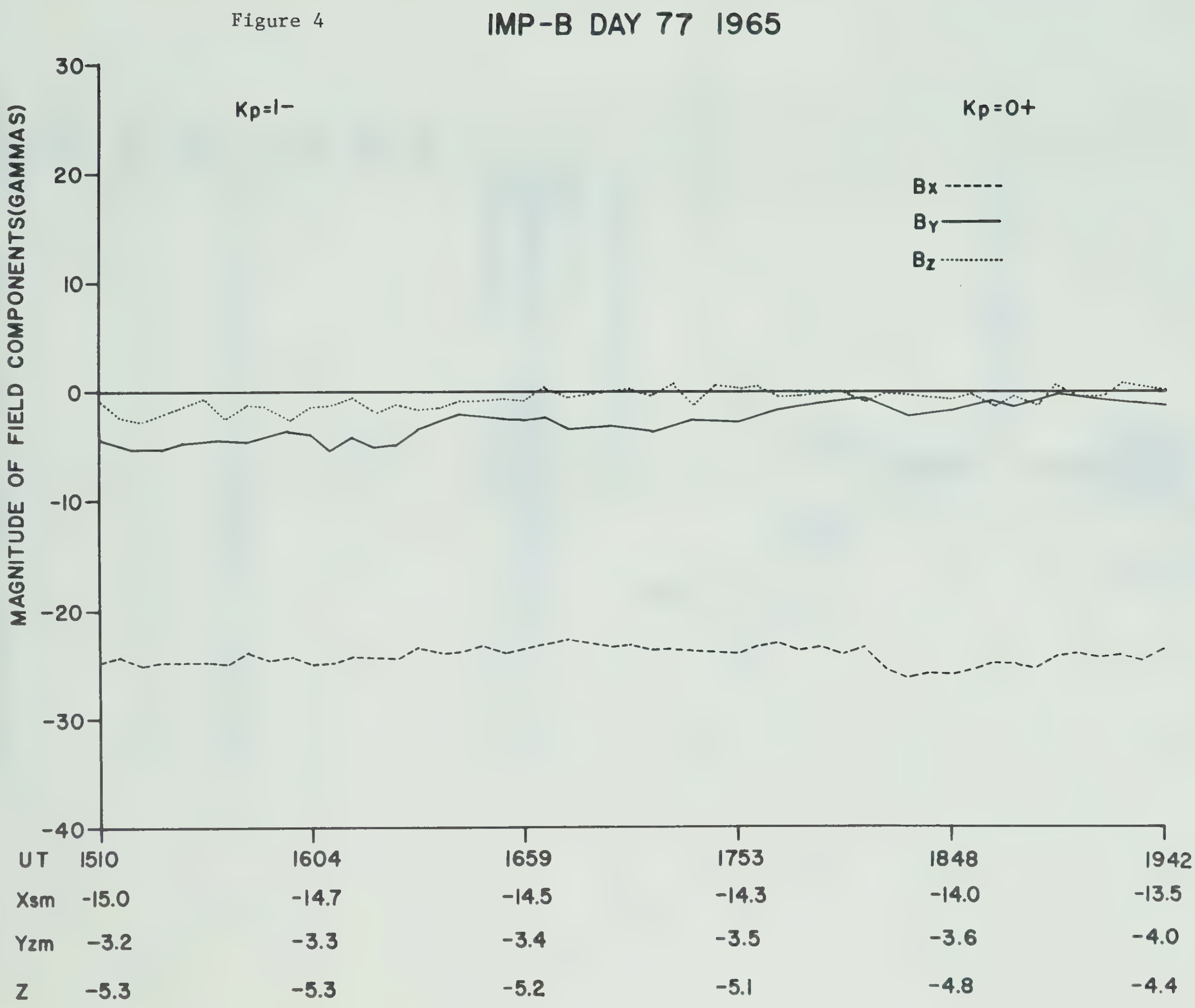
is more likely that the complex behaviour which is sometimes observed results from the satellite being poorly positioned with respect to the disturbed region, so that it observes these and possibly other extraneous effects through hydromagnetic wave propagation.

The clarity with which the effects in (2) and (3) above may be observed can range from that shown in the examples in this paper to being barely detectable above the background noise. Responses are seen at distances from 12 to 31 Re down the tail, although the character of the response changes over this range. Typically within ~15 Re, the magnetic field effect is sluggish (see Figure 8) by comparison with that observed at greater radial distances (see Figure 7). In general, the Imp B events are of longer duration than the Imp A events. This is particularly true with respect to the return of the magnetic field to its pre-substorm orientation and intensity. These observations are illustrated in Figures 7 - 12.

Figure 4 is included to illustrate the magnetotail field during magnetically quiet periods on the surface of the Earth, as indicated by the value of the Kp index in the figure. The components of the magnetic field in the solar ecliptic system are plotted here as a function of time. The large X component is typical of the tail field configuration. The position of the satellite is defined by the values of Xsm, Ysm, and Z in the co-ordinate system defined earlier.

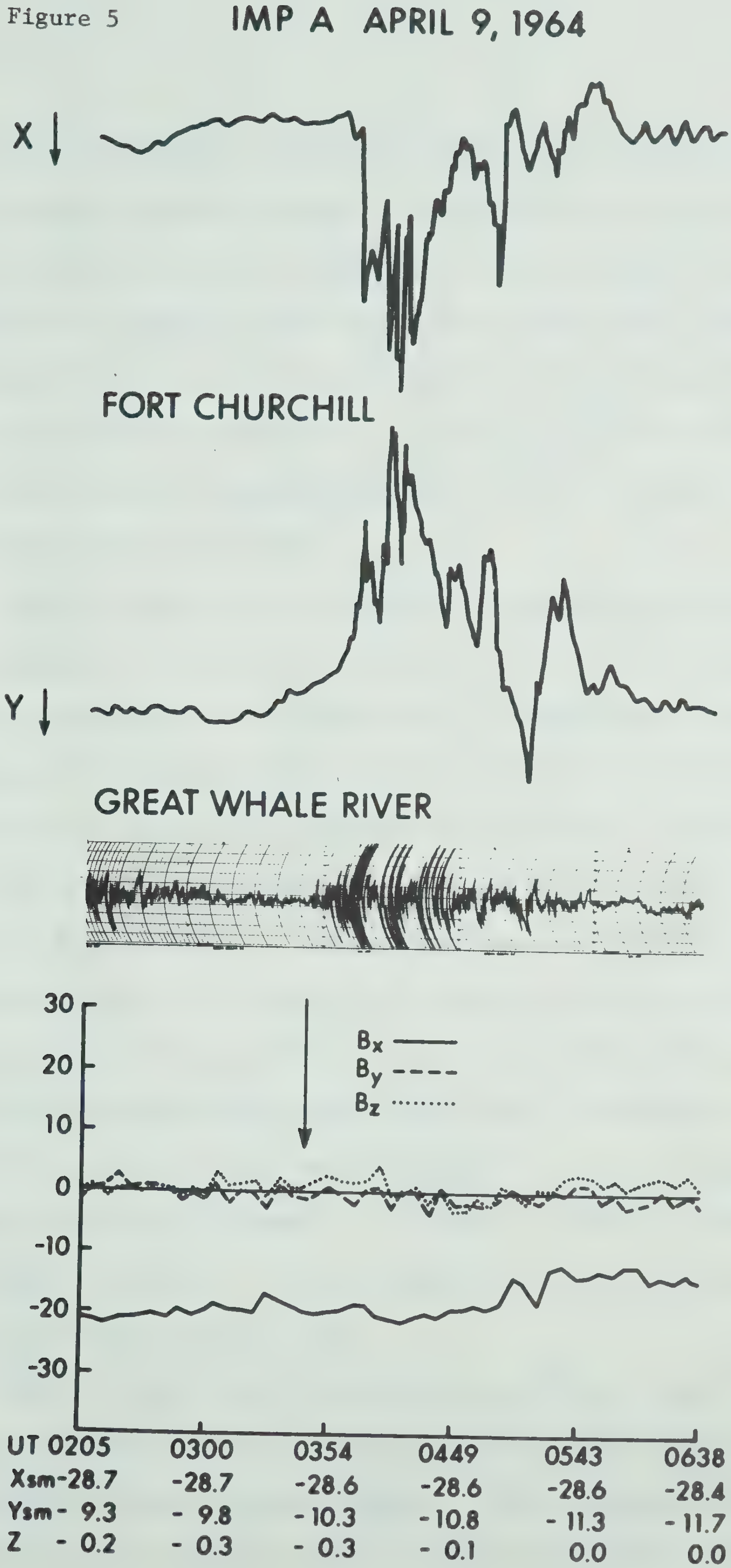
Figure 5 may be compared with Figure 4. Here at least three distinct Pi2 onsets can be identified between 0345 UT and 0500 UT from the rapid run magnetograms at Great Whale River. From the X and Y geomag-

Figure 4



IMP-B DAY 77 1965
Kp=1−
Kp=0+
Bx
By
Bz
MAGNITUDE OF FIELD COMPONENTS(GAMMAS)
30
20
10
0
-10
-20
-30
-40
UT 1510 1604 1659 1753 1848 1942
Xsm -15.0 -14.7 -14.5 -14.3 -14.0 -13.5
Yzm -3.2 -3.3 -3.4 -3.5 -3.6 -4.0
Z -5.3 -5.3 -5.2 -5.1 -4.8 -4.4

Figure 5

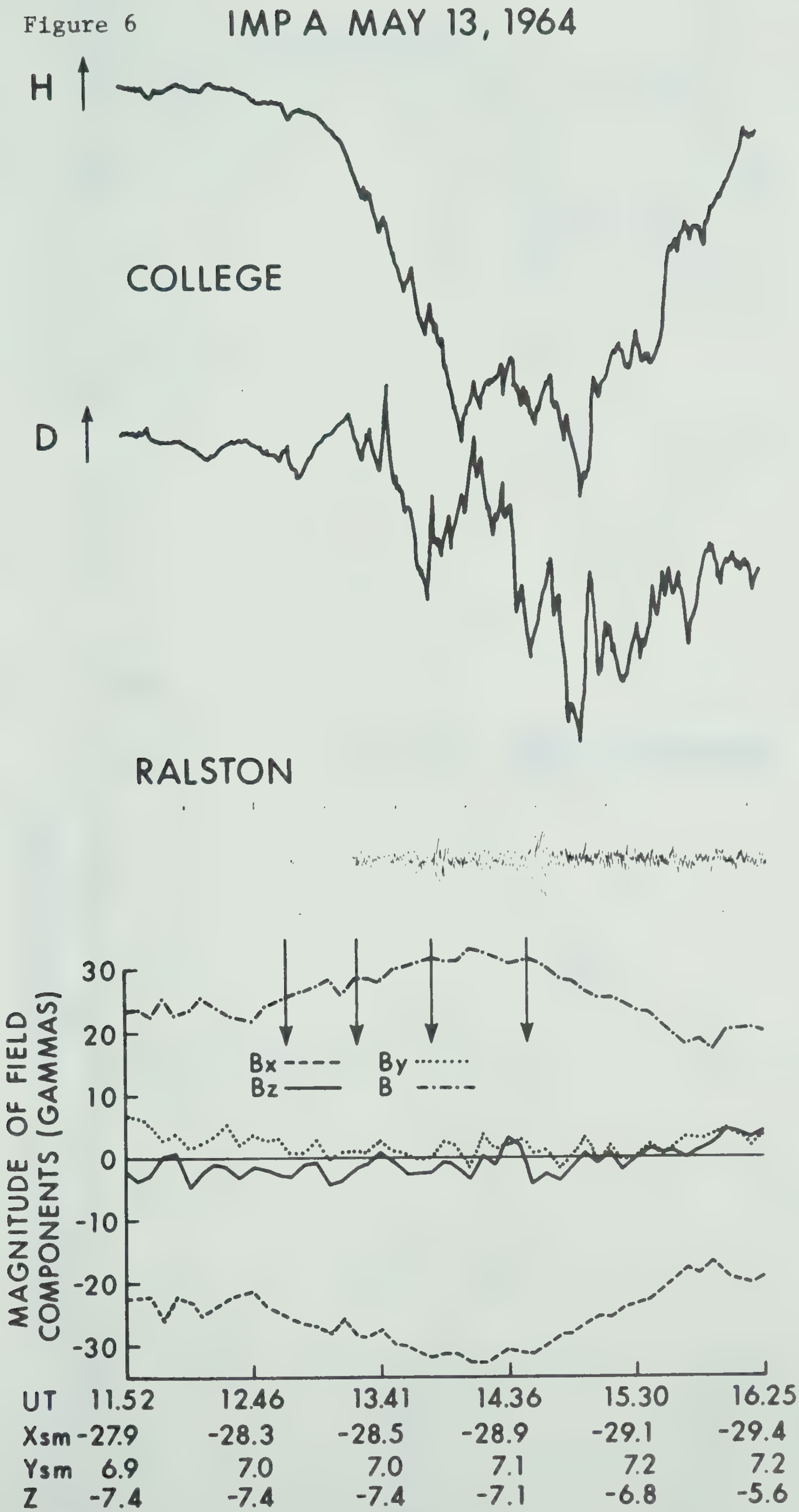

IMP A APRIL 9, 1964
X
FORT CHURCHILL
Y
GREAT WHALE RIVER
30
20
10
0
-10
-20
-30
Bx
By
Bz
UT 0205
0300
0354
0449
0543
0638
Xsm-28.7
-28.7
-28.6
-28.6
-28.6
-28.4
Ysm- 9.3
- 9.8
- 10.3
- 10.8
- 11.3
- 11.7
Z - 0.2
- 0.3
- 0.3
- 0.1
0.0
0.0

netic field components at Fort Churchill, these are clearly associated with isolated substorm activity. Furthermore, at the satellite some 28.6 Re down the tail and close to the neutral sheet, the time variations in the magnetic field during this time are not significantly different from those in Figure 4 during magnetically quiet conditions. Thus one is led to conclude that, at least at certain locations within the tail, there is no magnetic manifestation of the magnetospheric substorm above the noise level.

That the field in the magnetotail may become more "tail-like" (i.e., its components in the solar magnetospheric Z and Y directions become a smaller proportion of the total field) is demonstrated in Figure 6. Here a substorm is observed in the H and D components of the College magnetogram and Pi2 onsets are identified from the Ralston rapid run magnetogram at 1301, 1329, 1403 and 1444 UT. The satellite,located about 28.5 Re from the Earth,records an increasing X component without any proportional increase in the Y or Z components during the period bracketing the first three onsets. This is typical of the form of the tail response described by Behannon and Ness (1966) prior to geomagnetic storm conditions; that is, an overall increase in the field magnitude seen primarily in the X component. The field is therefore becoming more tail-like. Figures 7 - 9 show magnetotail effects for substorms having only one identifiable Pi2 onset.

Figure 7 shows data collected by Imp A at the time of a substorm (illustrated by the H and D components at College) which features excursions of several hundred gammas. This substorm, although large, is not part of a magnetic storm. Indeed, it appears to be isolated

Figure 6


IMP A MAY 13, 1964
H
D
COLLEGE
RALSTON
Bx
By
Bz
B
MAGNITUDE OF FIELD COMPONENTS (GAMMAS)
30
20
10
0
-10
-20
-30
UT 11.52 12.46 13.41 14.36 15.30 16.25
Xsm -27.9 -28.3 -28.5 -28.9 -29.1 -29.4
Ysm 6.9 7.0 7.0 7.1 7.2 7.2
Z -7.4 -7.4 -7.4 -7.1 -6.8 -5.6

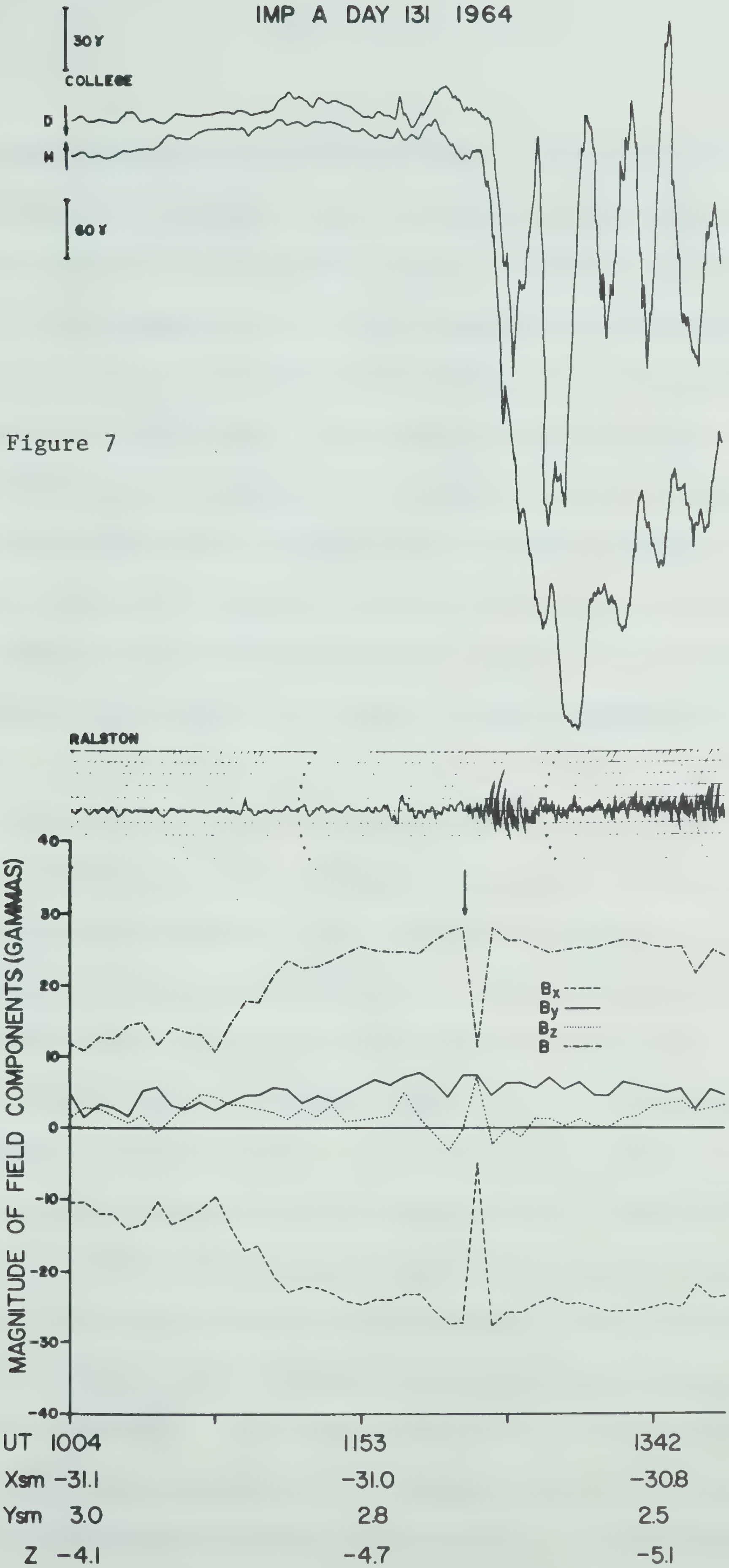

IMP A DAY 131 1964
30γ
COLLEGE
D
H
60γ
RALSTON
MAGNITUDE OF FIELD COMPONENTS (GAMMAS)
40
30
20
10
0
-10
-20
-30
-40
B_x
B_y
B_z
B
UT 1004
1153
1342
Xsm -31.1
-31.0
-30.8
Ysm 3.0
2.8
2.5
Z -4.1
-4.7
-5.1

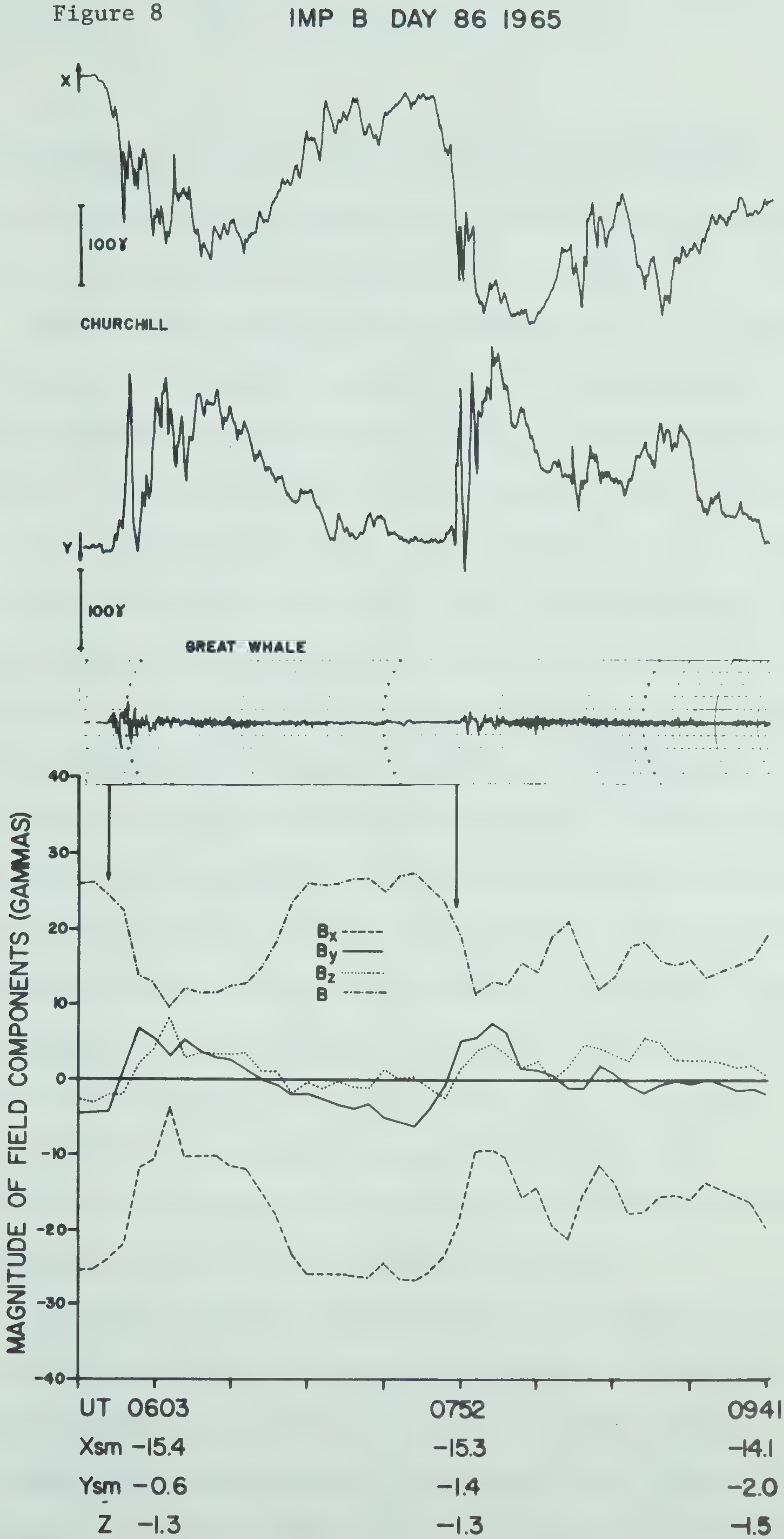
Figure 7

with respect to other magnetic activity. The onset time is given by the Pi2 burst at Ralston. The satellite at ~ 31 Re down the tail experiences, coincident with the Pi2 onset, a reduction of the total field B and of the X component Bx. The Z component Bz, previously of the order of one-tenth of the total tail field, is now a considerably larger proportion of that field. Two other features are worthy of note. The field effect at the satellite is confined to the early part of the substorm, with the field returning to its previous configuration within 10 minutes after the Pi2 onset in spite of continuing substorm activity. Also, approximately 2 hours before the substorm, the field builds up to an enhanced value which it retains up to and subsequent to the substorm.

This field build-up may also be compared with similar results found by Behannon and Ness (1966) prior to storm activity. Indeed, it would seem from Figure 7 that the input of energy into the tail field commenced at approximately 1100 UT (as indicated by the increasing tail field magnitude) and continued until the substorm onset.

Figure 8 shows two substorms represented by X and Y magnetic field components at Fort Churchill. The magnetotail field data here are from the Imp B satellite ~15 Re down the tail. Again, there is a reduction in B and Bx, and an increase in Bz coincident with the Pi2 onsets. There is also a distinct response in the Y component in these cases. However, this Y component perturbation has the same sign as that of the Z component. It follows, therefore, from the earlier discussion that in the solar magnetospheric reference frame the value of the Z component perturbation would be even larger. It should be noted that

Figure 8


IMP B DAY 86 1965
X
100γ
CHURCHILL
Y
100γ
GREAT WHALE
MAGNITUDE OF FIELD COMPONENTS (GAMMAS)
40
30
20
10
0
-10
-20
-30
-40
Bx
By
Bz
B
UT 0603
0752
0941
Xsm -15.4
-15.3
-14.1
Ysm -0.6
-1.4
-2.0
Z -1.3
-1.3
-1.5

the response is much more sluggish than the typical response at greater radial distances, and the magnetotail and ground based substorm observations last approximately the same length of time.

Figure 9 shows the magnetotail responses for three large substorms in the midst of an intense magnetic storm. The geomagnetic activity is represented by the H component at Byrd and the D component at College. However, the rapid run magnetogram shows Pi2 bursts only for the first and third substorms. The occurrence of these micropulsations at all at this station testifies to their large magnitude, as all the events occur several hours before local geomagnetic midnight at Great Whale River. The Pi2 burst for the first substorm seems immersed in other micropulsation activity. However, there is a clear change of character at this point allowing an acceptably accurate estimate of the onset time to be obtained. For the first two events, a transfer of field from the X to the positive Z direction is clearly observed. The third substorm onset affords a good example of transfer of field from the X direction to the negative Z direction, i.e., the opposite direction to that expected from field lines rooted in the Earth. Also noticeable in this diagram, by comparison with the others, is the smaller reduction of total field for all three events, although this reduction is reasonably clear for the first and third events.

Convincing evidence of magnetotail effects synchronous with the second Pi2 onset within a substorm is presented in Figure 10. This would correspond to the main bay onset of Rostoker (1968). Although the normal magnetogram data were limited for this event to the X and Y components at Fort Churchill, these are adequate to establish the

Figure 9 IMP A DAY 92-93 1964

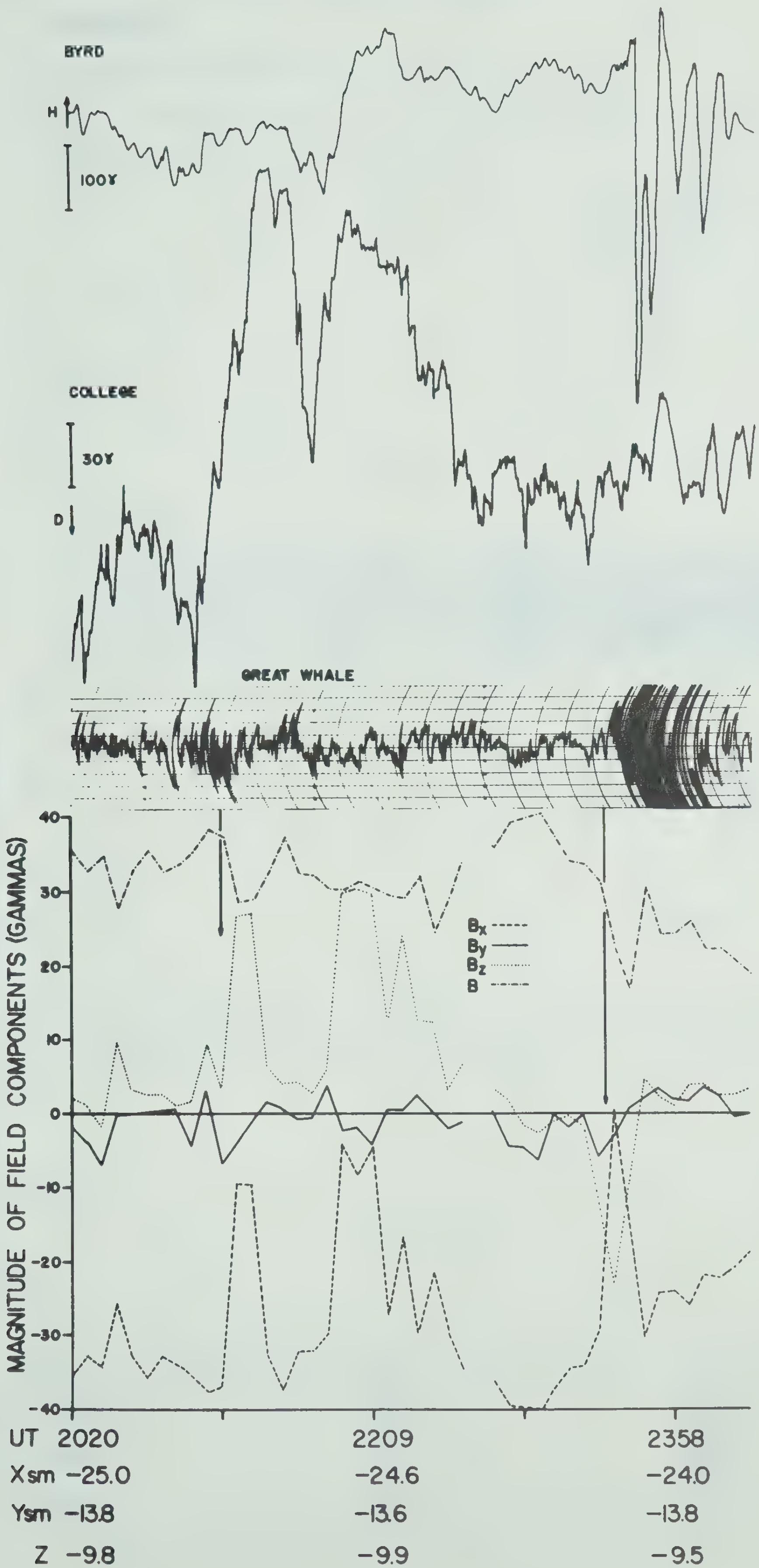
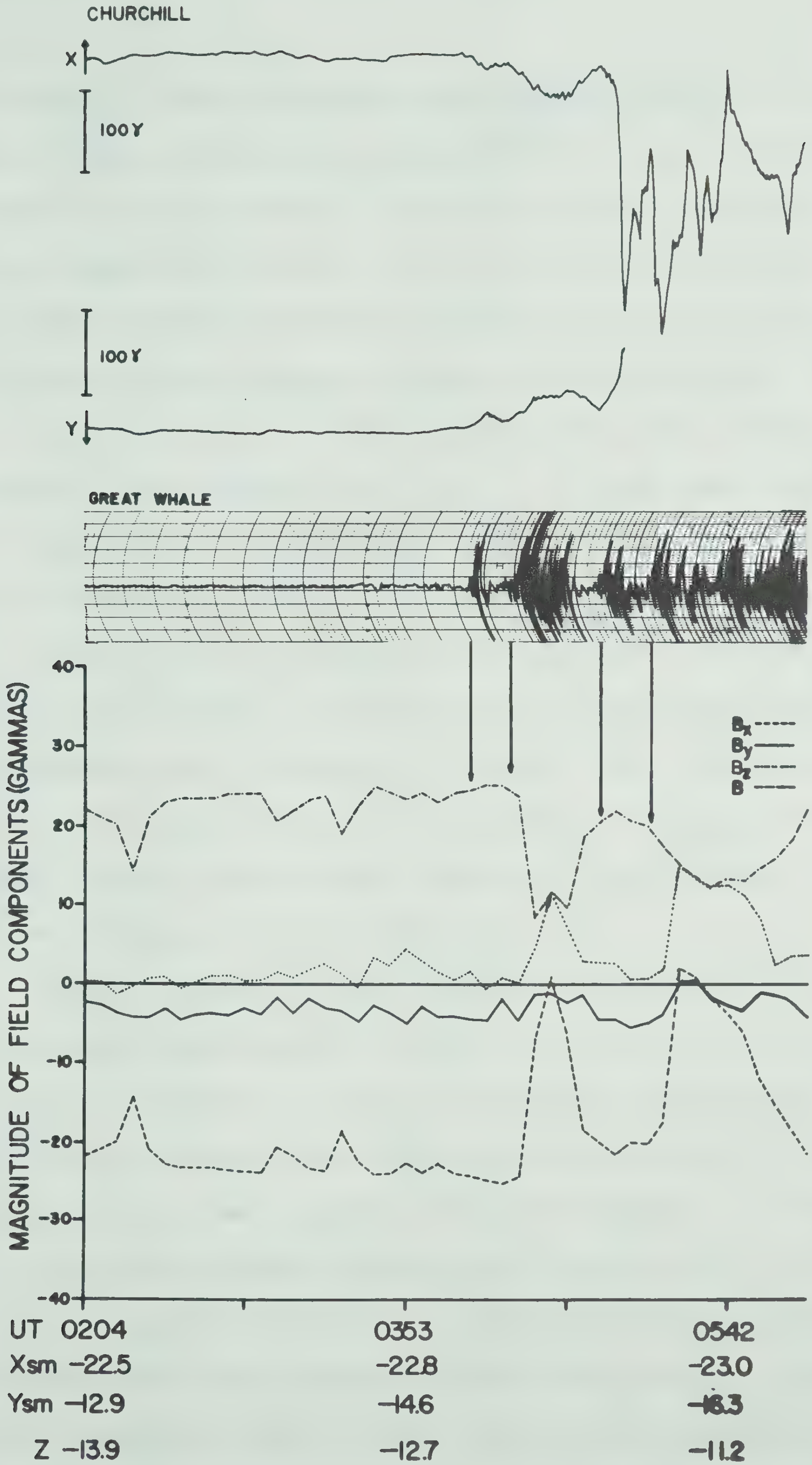


Figure 10

IMP A DAY 80 1964



existence of substorm activity corresponding to the Pi2 onsets at Great Whale River, at 0416, 0431, 0502 and 0520 UT. The satellite is at a distance of ~23 Re down-tail and observes distinct reductions in Bx and B with associated increases in Bz at the second and fourth Pi2 onsets. One cannot in this case establish whether one has two separate substorms each showing a tail response coincident with the second Pi2 onset within the substorm, or only one substorm within which tail responses are observed at the third and fourth onset. In either case, the possibility of a response in the tail with the second Pi2 onset in the absence of such a response with the first Pi2 onset is clearly established.

Figure 11 shows an example of a substorm with three distinct Pi2 bursts as represented by the Byrd rapid run magnetogram and the H and D component traces at Reykjavik. Clearly, there is no effect in the tail at 14 Re associated with the first Pi2. At the second and third onsets, typical tail behaviour is observed (i.e., a transfer from the X to the Z component coincident with the onsets).

Finally, Figure 12 has been included as an example of the indications seen occasionally of effects in the tail field late in the development of a substorm. It may be noted that no correlation is shown with the Pi2 activity, but at 0820 UT at the position of the dotted line, there is a small transfer into the Z component. The Fort Churchill X and Z traces shown indicate that the substorm was still in its expansive phase at this time (i.e., the absolute values of the perturbations were still progressing towards their maxima). Typically, the Pi2 onsets are associated with a sharp intensification of the magnetic field perturbation as observed at stations close to the substorm

Figure 11

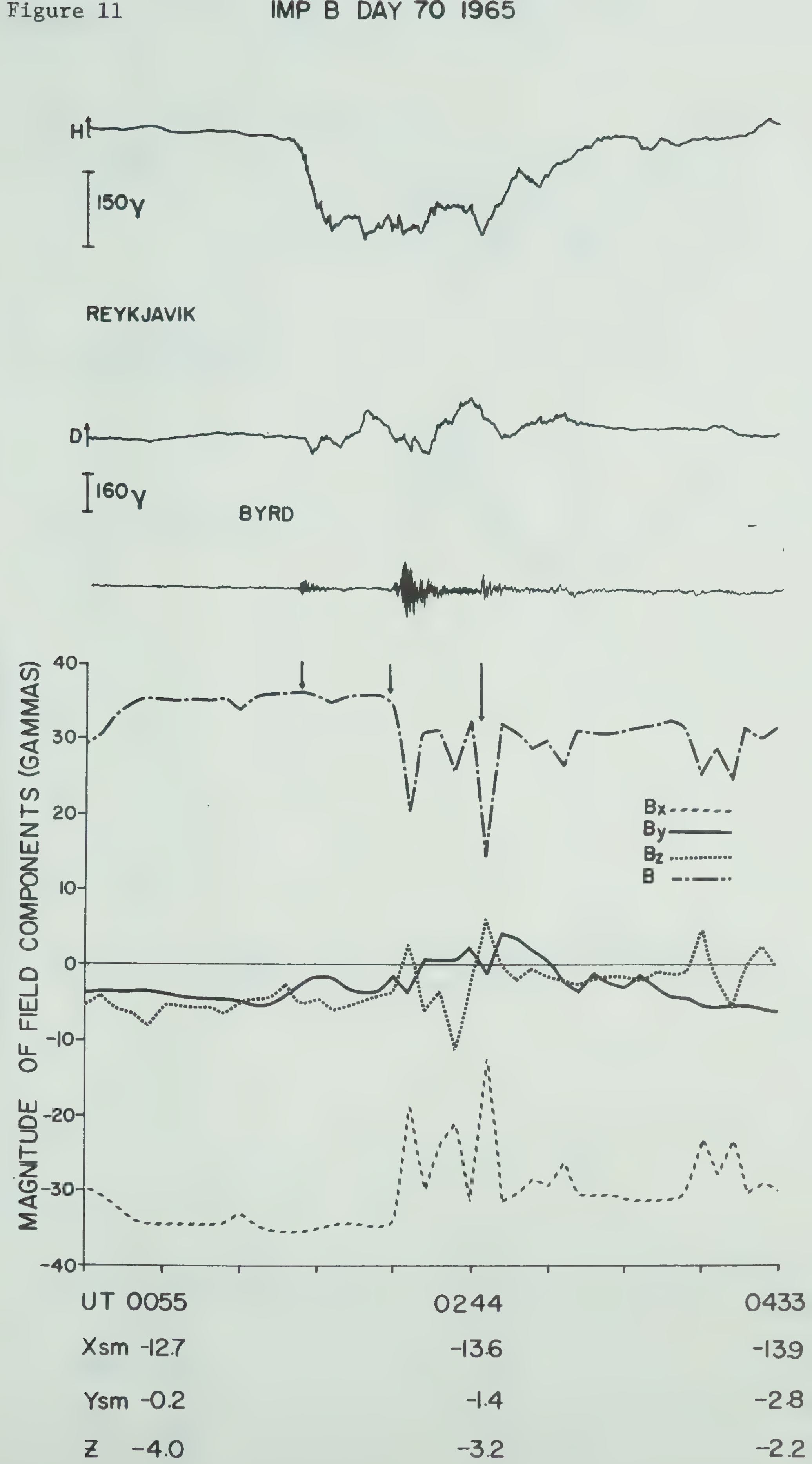
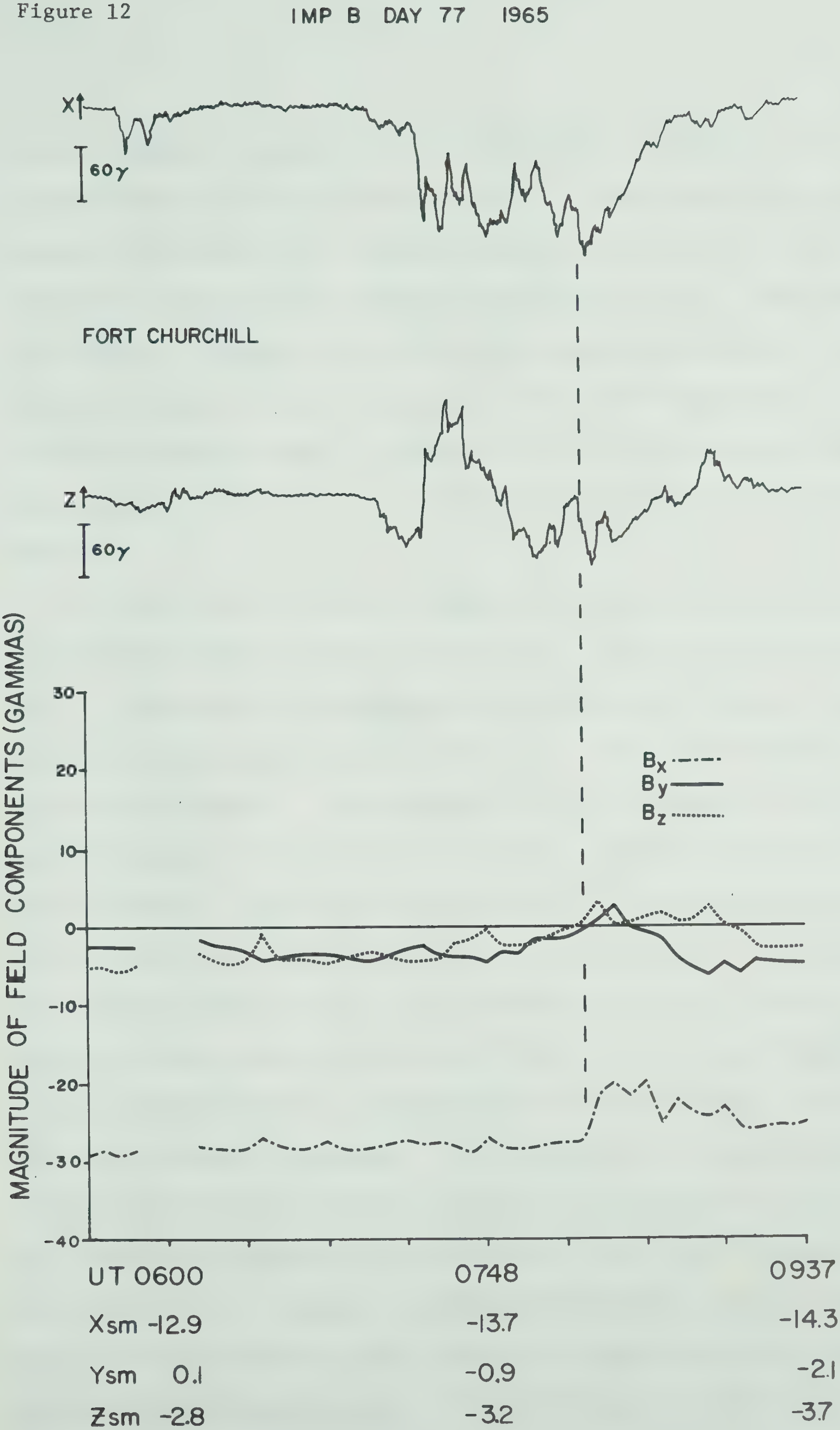

IMP B DAY 70 1965
H
150γ
REYKJAVIK
D
160γ
BYRD
MAGNITUDE OF FIELD COMPONENTS (GAMMAS)
40
30
20
10
0
-10
-20
-30
-40
Bx
By
Bz
B
UT 0055
0244
0433
Xsm -12.7
-13.6
-13.9
Ysm -0.2
-1.4
-2.8
Z -4.0
-3.2
-2.2

Figure 12


IMP B DAY 77 1965
X
60γ
FORT CHURCHILL
Z
60γ
MAGNITUDE OF FIELD COMPONENTS (GAMMAS)
30
20
10
0
-10
-20
-30
-40
Bx
By
Bz
UT 0600
0748
0937
Xsm -12.9
-13.7
-14.3
Ysm 0.1
-0.9
-2.1
Zsm -2.8
-3.2
-3.7

current system. Between such intensifications the magnitude of these perturbations may tend to decrease slowly. Each intensification represents an increase in the current intensity and an input of energy at each onset as discussed by Kisabeth and Rostoker (1971). Away from this region, this simple form of the magnetogram trace becomes distorted; hence, one sees the inadequate nature of the normal magnetogram to establish accurate onsets. However, the form of the X trace suggests that several of the periodic intensifications may have occurred before 0820 UT.

To study the correlation of magnetotail field effects with satellite position, the changes in Bx, By and Bz were noted for all decreases of Bx > 5 γ associated with substorm onsets as described earlier. Each of these was then plotted as a function of each of the directions Xsm, Ysm, and Z defined earlier. ΔBz and ΔBx plotted as functions of Xsm are shown in Figures 13 and 14. All other plots showed comparatively random distributions. The trends shown in Figures 13 and 14 become more apparent in Figure 15. This figure consists of three plots. The first shows the average values of ΔBx, and the standard deviation for intervals containing 15 data points, as a function of Xsm. For the same intervals the average values of positive ΔBz and negative ΔBz are plotted together with the overall standard deviation. The third plot is of positive and negative ΔBz, and the total standard deviation in intervals of 2 Re, displayed as a function of Xsm, when the satellite lay close to the sun-earth line and when Kp $\leq$ 1+. As might be expected from previous results, comparison of the two ΔBz plots shows consistently higher values for those correlated with substorm onsets. It is noticeable, however, that there

Figure 13

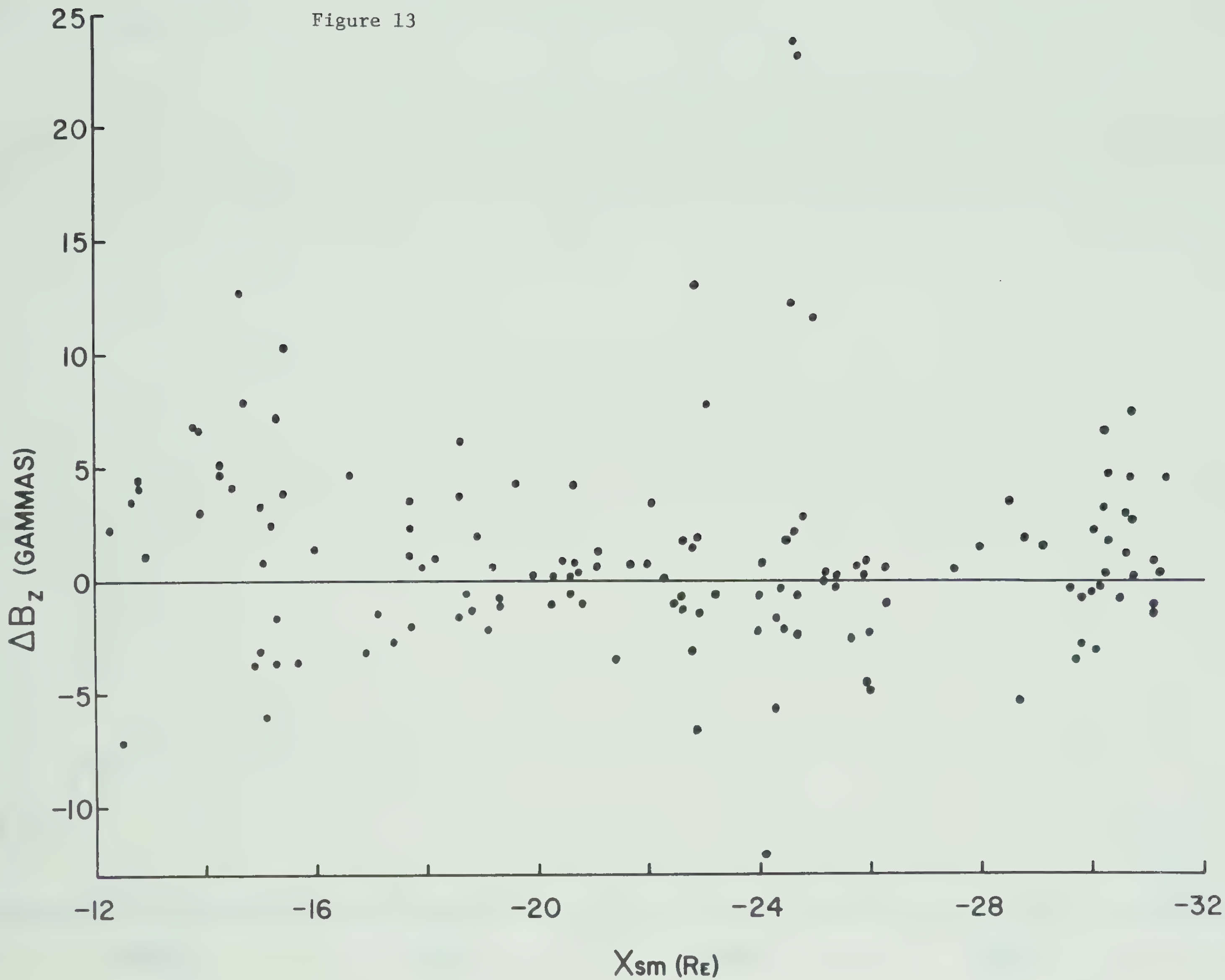
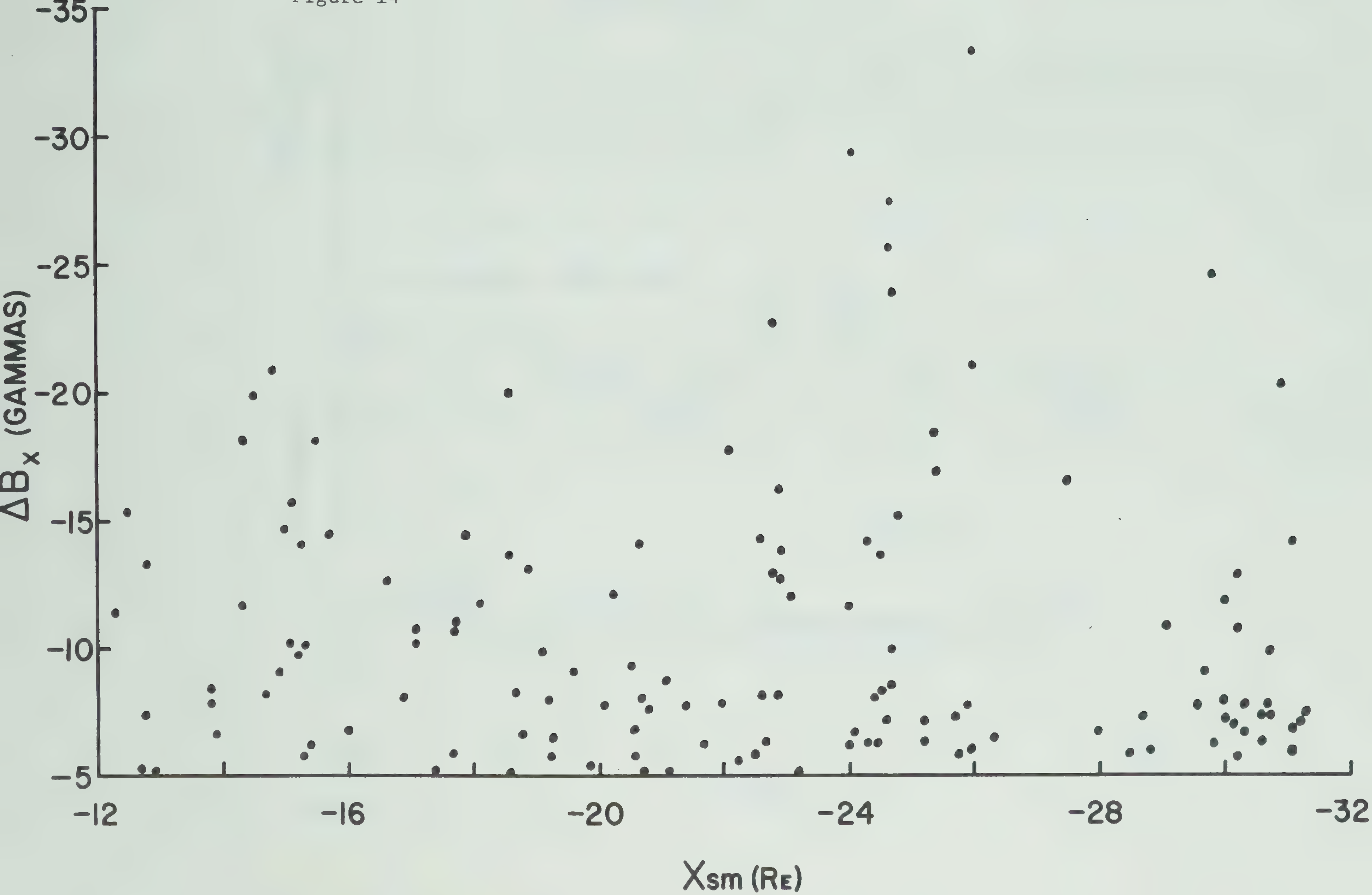


Figure 14



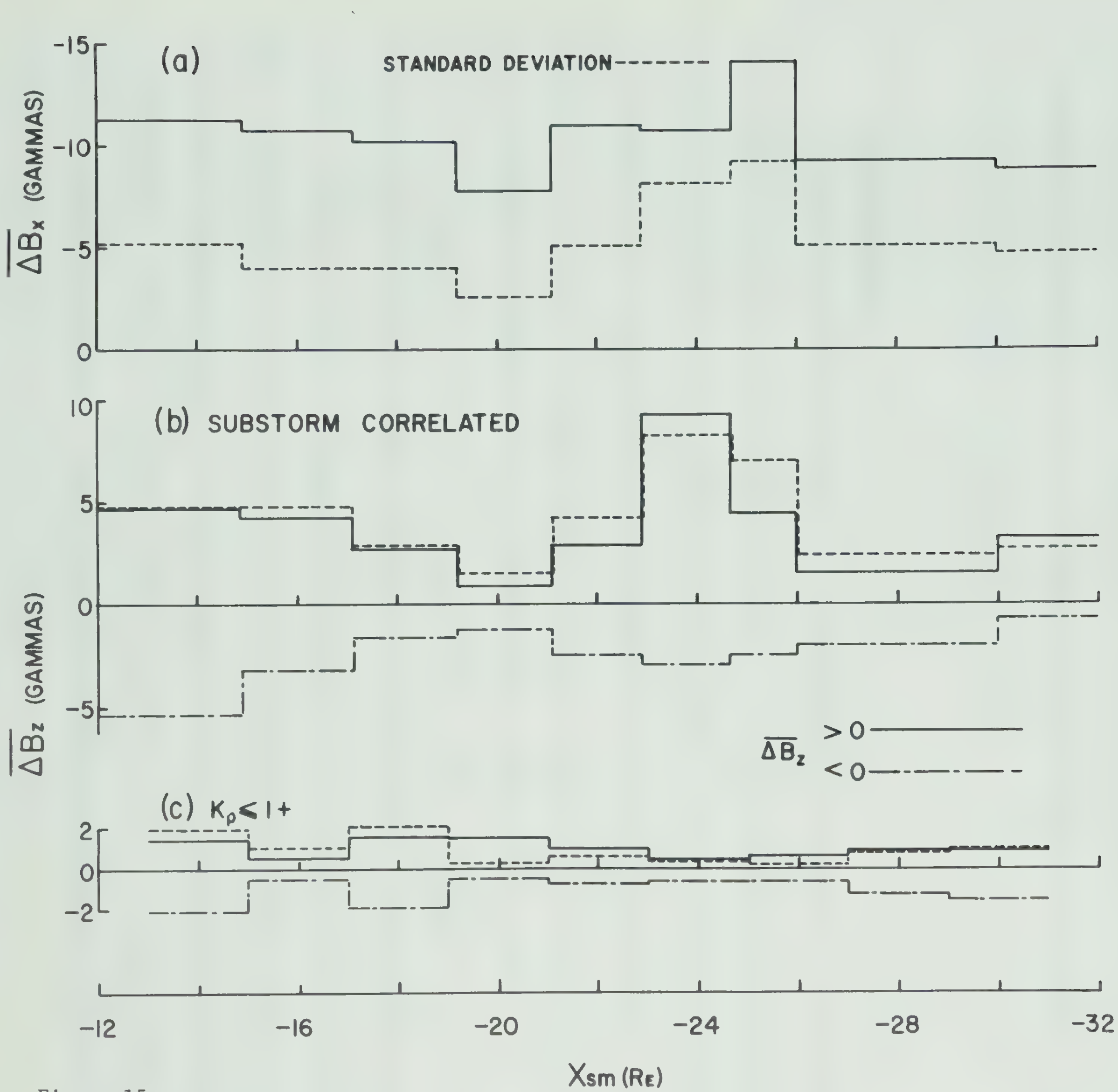

(a)
STANDARD DEVIATION
$\overline{\Delta B_x}$ (GAMMAS)
-15
-10
-5
0
(b) SUBSTORM CORRELATED
$\overline{\Delta B_z}$ (GAMMAS)
10
5
0
-5
$\overline{\Delta B_z}$ > 0
< 0
(c) $K_p \leq 1+$
2
0
-2
-12
-16
-20
-24
-28
-32
Xsm (RE)

Figure 15

exists a peak in the substorm correlated plot between 21 and 26 Re. The greater part of this peak is contributed by the positive average ΔBz reflecting the more frequent occurrence of positive ΔBz. It can also be seen that there is a blowup of both positive and negative ΔBz at low values of Xsm. Finally, it should be noted that ΔBx shows a tendency to maximize between 21 and 26 Re, although it is less distinct than the corresponding effect in ΔBz.

2.4 Interpretation

In the following discussion, consideration of onsets for which no tail effect is observed will be deferred. It is suggested that observations of tail field perturbations synchronous with substorm-associated Pi2 onsets may be explained by the field line reconnection model. In particular, the large negative excursions of Bz observed around 24 Re are difficult to explain by any other model suggested to date.

The currents required to be consistent with the existence of the magnetotail naturally depend critically on the magnetic field topology. If one takes as a model a magnetic field with a circular cross section, the top half circle intersected by field directed towards the sun and the lower half circle by field directed away from the sun, the currents required must follow the pattern shown in Figure 16(a) (looking down the tail towards the Earth). Such a model has been presented by Axford et al. (1965).

From our observations, it would seem that a substorm onset may be associated with a reduction in the magnitude of the tail field. This requires a reduction in current, which is equivalent to adding the current

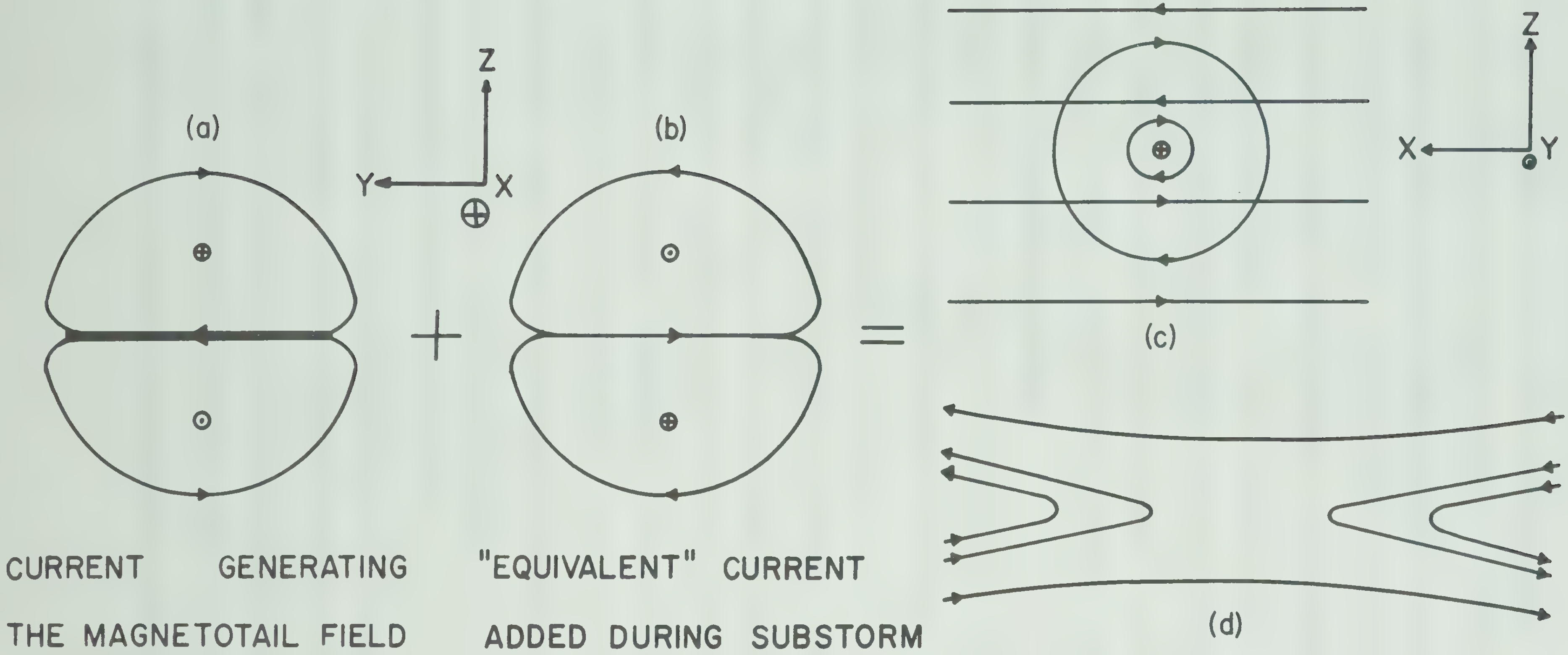

(a)
(b)
(c)
(d)
Z
Y
X
CURRENT GENERATING
THE MAGNETOTAIL FIELD
"EQUIVALENT" CURRENT
ADDED DURING SUBSTORM

Figure 16

system shown in Figure 16(b) to that shown in Figure 16(a). However, in order to obtain fields in the Z direction as observed, the equivalent current system shown in Figure 16(b) must be, at least initially, localized in the Xsm direction. Looking along the Ysm axis the fields associated with the currents shown in Figure 16(a) and Figure 16(b) would be those shown in Figure 16(c). This configuration is, of course, equivalent to that shown in Figure 16(d), which is the familiar reconnection picture. What is attractive about this model is that the southward field component producing negative ΔBz, which is a natural feature of the process, is distinctly observed.

Subsequent to their reconnection, the field lines might be expected to vacate the region of merging together with plasma frozen to them by contracting in the Xsm direction under the effective tensional forces in the field lines (Alfvén and Fälthammar, 1963). This would allow the field rotation from Bx to Bz to be observed throughout the length of the tail, and at varying distances from the neutral sheet depending on the number of lines that reconnect. The loss of this plasma would cause a pressure imbalance allowing the surrounding plasma and "frozen-in" unconnected field lines to collapse into the hole left by the evacuating reconnected lines, thus re-establishing the original field configuration (which is observed to occur).

It is suggested that the above outline is a model consistent with the results obtained. If this is in fact the case, it would seem that increased tail flux during storm time observed by Behannon and Ness is relieved to some extent by the substorm events. If the effect of the field increasing in the manner they observed is simultaneously countered

by the reduction due to reconnection, then during storm time the change in the total field magnitude at the onset of reconnection would be expected to depend on which dominates. The reader is referred to Figure 9 where it was mentioned earlier that the reduction of total field was not striking. Whether or not a net reduction of the tail field results on its return to the pre-substorm configuration depends on the balance between the amount of flux removed from the tail through the substorm process and the amount of flux added to the tail during that time. For example, no perceptible reduction in tail field ensues from the substorm processes shown in Figures 7 and 10. On the other hand, the second substorm effect in Figure 8, the third substorm effect in Figure 9 and the second substorm effect in Figure 11 all entail a net reduction in tail field.

With reference to the correlation of tail field effects with the position of the satellite, the plots should be interpreted with some care. If one assumes that the perturbations in the field components are largest in the region of reconnection, the results would imply that reconnection occurs in the range of the bulge between 21 and 26 Re. However, most of the large perturbations in the bulge occur during storm time when it is expected theoretically that any reconnection would occur nearer the Earth (Unti and Atkinson, 1968). Also, the reconnection process during storm time may be expected to produce larger perturbations. It is suggested then that reconnection occurs over a range in the Xsm direction such that the earthward side of this bulge is the innermost limit of this range, the upper limit being indeterminable from our data.

In addition to the blowup of ΔBz outside ~ 21 Re, we have shown that ΔBz gets larger as one approaches the Earth. The direction of the change can be either positive or negative although positive changes appear to dominate slightly. It is considered that the increase in magnitude of ΔBz as one approaches the Earth reflects the increase in the ambient B field. The sign of this change, however, depends on the geometry of the distended field lines relative to the undistended dipole configuration, and the following considerations must be kept in mind while employing the reconnection model to interpret these data.

Figure 17 shows two unconnected field lines which, it is suggested, will, through reconnection, collapse into a single more dipolar field line in the position shown by the dotted line. The line $Xsm = R_1$ intersects the solid and dotted lines at points where they have the same gradient. $Xsm = R_2$ represents the inner boundary of the range in which the unconnected field lines may be considered to have a negligible Z component. The sign of ΔBz will depend on which region the satellite is in at this time. In the region $Xsm < R_1$, the rotational effect will cause $\Delta Bz < 0$ above and below the neutral sheet. In the region $R_1 < Xsm < R_2$ one would expect $\Delta Bz > 0$ through rotation unless the tail field decrease dominates, in which case one would observe $\Delta Bz < 0$.

However, the value of R_1 depends on the particular pair of lines chosen. Thus, the value of Xsm below which only $\Delta Bz < 0$ is observed (i.e., $Xsm = R_1$) depends on the distance of the satellite from the neutral sheet. Therefore, no such effect appears in Figures 13 and 14 where the value of the neutral sheet distance from the satellite varies. In summary for $Xsm < R_2$ one would observe $\Delta Bz < 0$ or $\Delta Bz > 0$ with the

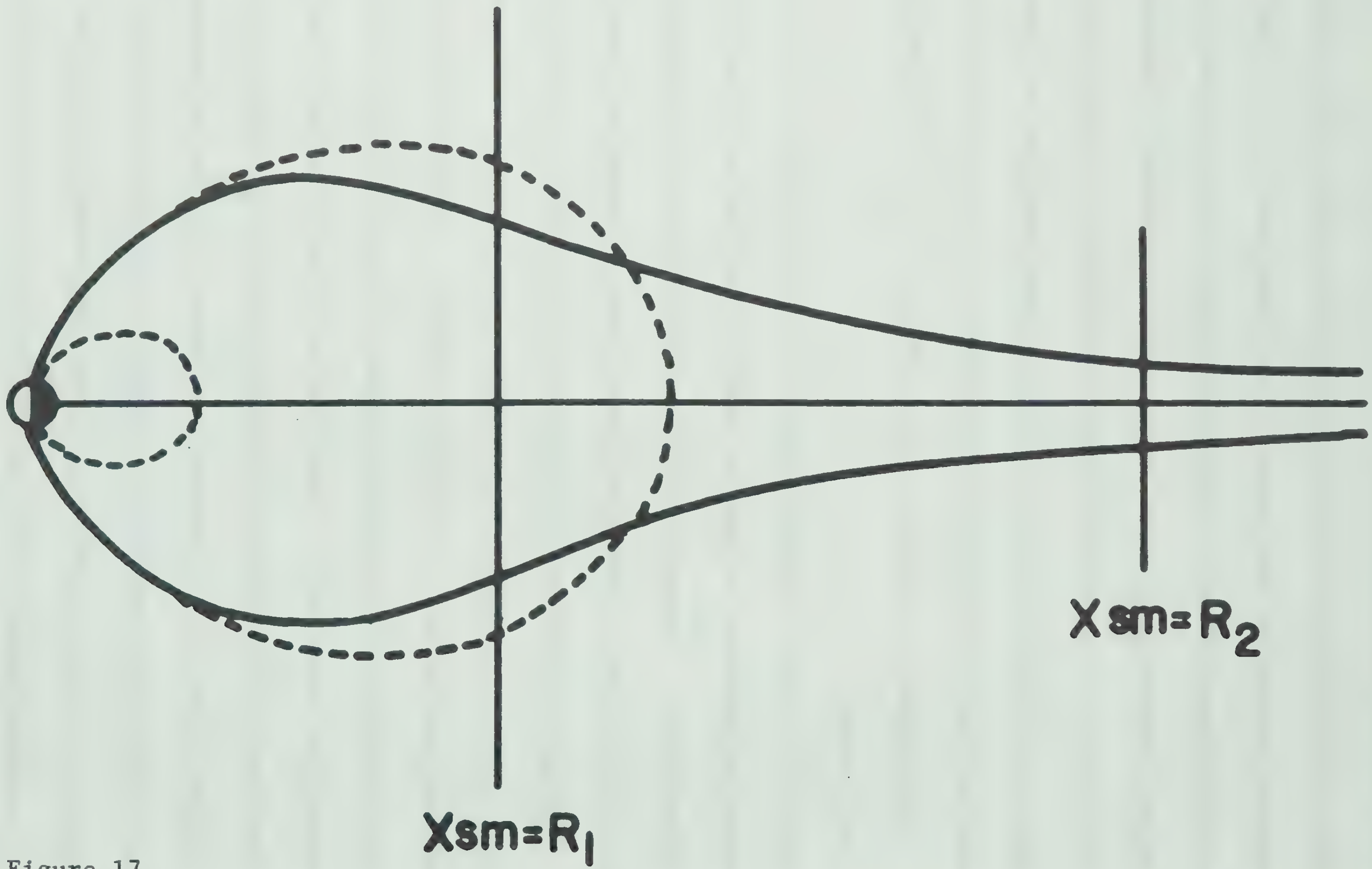


Figure 17

magnitude of $|\Delta Bz|$ being related to R_2 - Xsm.

Outside these regions where Xsm > R_2, the ambient value of Bz is near zero, so that changes in total field magnitude will not influence ΔBz substantially and the rotational effect always dominates. On the earthward side of the reconnection point (if this is somewhere beyond Xsm = R_2), ΔBz should always be positive, whereas on the other side of the reconnection point ΔBz should be negative. The fact that the reconnection point varies in position with magnetic storm activity suggests that, beyond the innermost edge of the reconnection range, one would expect to observe both positive and negative excursions in Bz.

It should be noted that the $\Delta Bz < 0$ for Xsm < R_2 would be observed if only previously connected field lines collapsed to a more dipolar configuration. However, in this case ΔBz would be a monatonically decreasing function of Xsm for Xsm < R_2 and ΔBz would be zero for Xsm $\geq R_2$. Thus, one cannot with this model explain the bulge between 21 and 26 Re.

The large ΔBz values in the range Xsm > 21 Re were explained previously on the assumption that larger Bz perturbations occur in the region of the reconnection. This follows from the fact that for some time prior to, and during, their reconnection the field lines approaching the reconnection region will have a substantial Z component. Bearing in mind that the reconnected field lines move away from the reconnection region more rapidly than they enter it, for values of Xsm outside this region, the flux in the Z direction will be spread out giving weaker ΔBz variations.

Also, it was pointed out that close to the Earth (inside ~15 Re)

the response of the magnetotail field is relatively sluggish, particularly in the recovery phase. This could be due to two possible effects. First of all the field change associated with the reconnection arrives over a longer period of time than the time over which reconnection occurs due to the spreading out of the field described in the previous paragraph. This would result in a somewhat greater time being required for the maximum ΔBz value to be reached while, in addition, enhanced Bz would be sustained for a longer period of time. Secondly, close to the Earth the solar wind becomes less effective in influencing the movement of field lines. In this region the effect of the Earth's dipole field becomes important in restricting field line motion. The net result is a slowing of the return to the pre-substorm configuration giving a longer recovery phase.

It is necessary now to consider, in the light of the model just developed, those events for which no magnetic field effect was observed at the satellite. The following are suggested as a comprehensive list of alternatives:

(1) It is possible that the field reductions and rotations resulting in the transfer of flux from the X to Z components observed coincident with the onsets identified are entirely fortuitous. It is felt that the number of clear examples of this, all showing synchronous earth-satellite effects within the accuracy of our measurements, make this a highly improbable explanation.

(2) It may be that the tail behaviour observed occurs throughout the whole magnetotail when observed by the satellite and not anywhere within the magnetotail when not observed at the satellite. That is to say,

it is associated with the substorm but does not always occur. For instance it may be a by-product of some other process in the magnetosphere which is responsible for the substorm phenomenon, and as such its presence may be determined by other peripheral conditions.

(3) It is possible that when an effect is observed at the satellite it does not necessarily occur throughout the whole of the magnetotail. It follows that if no substorm associated effect occurs at the satellite it is always occurring elsewhere in the tail. Some models consistent with this suggestion are discussed below.

It was pointed out earlier that a tail field collapse through reconnection would be seen anywhere within the volume containing the reconnecting lines. In the distant tail this volume is well approximated by a function which is independent of Xsm. As suggested earlier, it seems likely that the field lines above and below those which reconnect will move into the reconnection region to replace the reconnected lines which are vacating this region. As the fresh lines repopulate this region they may be expected to exhibit some rotation from Bx into Bz. Thus, this effect would be seen above and below the reconnecting lines. However, one would expect that the magnitude of the perturbation would be attenuated with increasing absolute values of the Z displacement of the satellite.

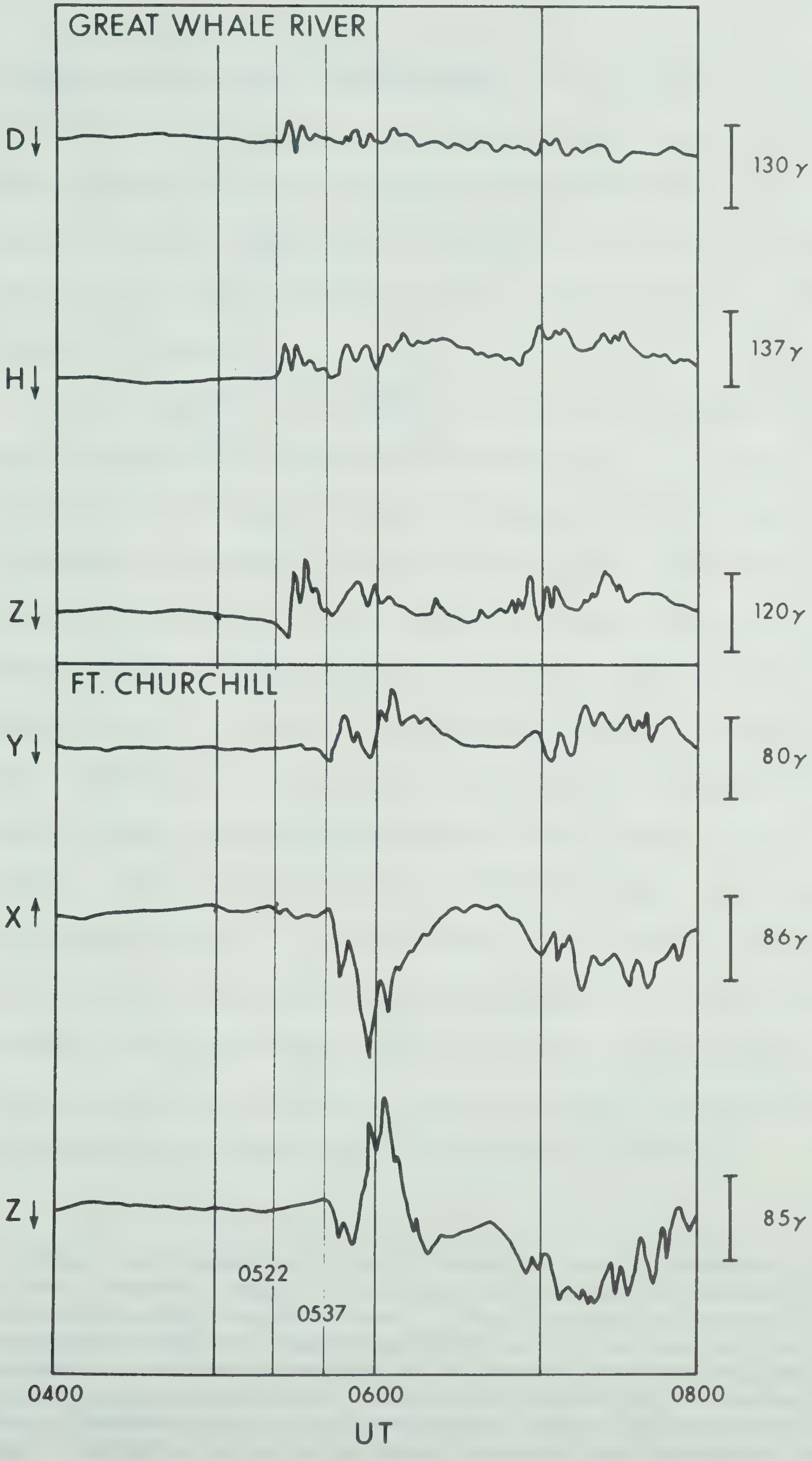
It is worth considering the implications of extending the model to include this inverse dependence on the Z displacement. It is indeed probable that the magnitude of the effect at a given value of Z will vary from substorm to substorm as a result of different total volumes of field reconnecting, thus creating differing total energy releases.

Therefore, one would not expect to see a simple relationship between the magnitude of the effect and the Z displacement. However, if this is so, it is difficult to see how, in Figure 5, with the satellite virtually in the neutral sheet (±2 Re, possible error in the Russell and Brody formula) the reconnecting volume could be so small as to show no effect here, if it is to achieve the necessary energy release from the magnetic field to create the substorm. Therefore it seems that the model discussed above is, alone, unable to account for all aspects of the tail magnetic field behaviour during substorms.

At this point, the only other possibility consistent with the suggestion that the effect is not uniform throughout the tail is that there exists a dependence of the magnitude of the perturbation on the Ysm direction. Such an extension to the reconnection model has been discussed by Rostoker and Camidge (1971) and it has certain features which make it attractive.

It is well known that after being initially centered around local geomagnetic midnight, the perturbation current system during the substorm usually increases its extent westwards. This development may occur quite rapidly and the leading edge of the current system is referred to as the westward travelling surge. Naturally, this leads to significantly different normal magnetogram traces at stations with different magnetic longitudes. An example of this is shown in Figure 18, where it is seen that distinct perturbations in the field at Great Whale River precede those at Fort Churchill (some thousand miles to the west) by about fifteen minutes. Given this westward progression of the ionospheric region in which energy is being deposited, it seems reasonable

Figure 18

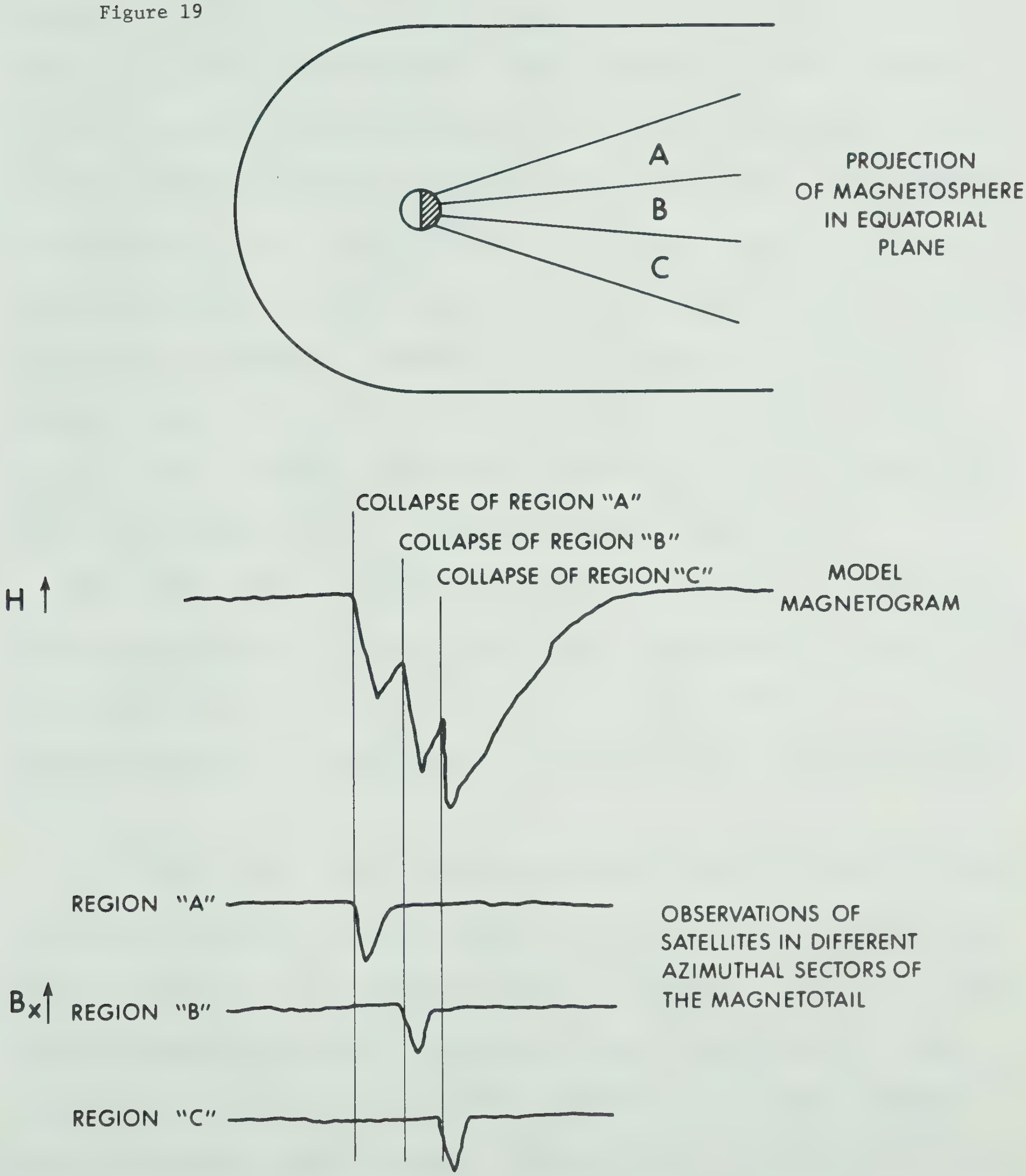

GREAT WHALE RIVER
D↓
130 γ
H↓
137 γ
Z↓
120 γ
FT. CHURCHILL
Y↓
80 γ
X↑
86 γ
Z↓
85 γ
0522
0537
0400
0600
0800
UT

to infer that one needs a magnetospheric energy source that progresses azimuthally. If indeed the reconnection in the tail is the mechanism which provides the substorm energy in the quasiperiodic manner observed, it seems likely that an azimuthal progression of the reconnection region occurs in discrete steps. This brings us to the model outlined in Figure 19.

It is suggested by the above authors that within the tail one may have a succession of azimuthally confined sectors A, B, and C collapsing in that order, the number of sectors being arbitrarily chosen as three to illustrate the model. This may be any number and may well vary from substorm to substorm. Such a development might produce an H trace on a typical night-time magnetogram in the auroral zone as shown by the model magnetogram in the figure. Note that the effect at the Earth due to each energy input is not finished when the next energy input occurs, thus one sees a continually deepening H trace in more or less discrete steps[†]. More significant here is the effect observed by satellites in the different sectors A, B, and C shown at the bottom of the figure. Here, only the typical reduction in the magnitude of $|Bx|$ is shown. However, the important factor is that a single satellite will only observe an effect in the tail in association with one of the intensifications of the current system and associated Pi2 onsets.

[†] Though this deepening of the H trace is commonly observed, it is not the only possible form of this trace, as substantial recovery may take place after each intensification. Thus, it must be realised that there are numerous magnetic signatures which can be recorded at the ground observatory that are dependent on the spatial and temporal development of each localised section of the auroral electrojet. However, each of these signatures may be explained by the model depicted in Figure 19 given a suitable choice of collapse frequency and development of the electric current system within the magnetosphere associated with the collapse of each region.

Figure 19


A
B
C
PROJECTION
OF MAGNETOSPHERE
IN EQUATORIAL
PLANE
COLLAPSE OF REGION "A"
COLLAPSE OF REGION "B"
COLLAPSE OF REGION "C"
H
MODEL
MAGNETOGRAM
REGION "A"
B_x
REGION "B"
REGION "C"
OBSERVATIONS OF
SATELLITES IN DIFFERENT
AZIMUTHAL SECTORS OF
THE MAGNETOTAIL

This model is adequate to describe the large majority of cases studied. However, Figure 11 indicates that it is possible to observe an effect at least twice coincident with two Pi2 onsets in the same substorm. If this is the case, then to retain this model one is forced to a further modification. One possibility is that regions A, B, C, etc., while representing a westward travelling energy source, may each collapse through reconnection more than once. Alternatively, the boundaries of say sectors A and B may be such that the two sectors overlap, providing a common region in which the collapse of both sectors A and B may be observed. However, in such speculations, one is straying rather far from the tangible evidence. Suffice it to say that this model provides a reasonable explanation for the intermittent lack of observable effects in the tail during substorms.

Two other points are worth mentioning with respect to this model. First, no dependence of ΔBx or ΔBz on Ysm is necessarily present as the character of the effect in any one sector for any substorm is consistent with the character of the effect in any other sector for any other substorm.

If, on the other hand, a substorm always starts in sector A, which is always in the same azimuthal range, and progresses through the same number of sectors at the same rate for all substorms, one might expect to find a dependence on the Pi2 number (i.e., first, second, third, etc.) within a substorm on azimuthal position. This was attempted, but no dependence could be seen. However, as it is difficult to find three or more distinct Pi2 onsets within a substorm, and of these only a few with the satellite suitably placed, this lack of dependence is by

no means established.

Secondly, as the data in the tail region were obtained in the region after 22.00 LT, any collapse of azimuthal sectors further round towards the dusk meridian would not be observed. Thus, from the restricted sampling region, if this model is correct, there is only a small probability of observing reconnection late in the substorm. This may explain the infrequence of such observations.

It was suggested earlier that, during storm time, the field reduction associated with a particular burst of reconnection in the tail may not be detectable, and further that the magnitude after the reconnection when compared with that before may not be perceptibly reduced if only a small amount of flux is removed. If the increased tail flux during a magnetic storm observed by Behannon and Ness is a result of a greater rate of addition of flux to the tail than under quiet conditions, this suggests that this addition rate is balanced by a high rate of removal of flux by a rapid succession of implosive merging events, producing the storm. Also, Figure 7 shows a distinct increase in field magnitude in the two hours preceding this isolated substorm.

It is postulated that the build-up of flux in the tail is directly or indirectly associated with the conditions favourable for substorms, and further that the rate of addition determines whether the substorms, being the agent of flux removal, will occur frequently enough to create a storm or appear only as isolated bursts. If this is indeed the case, then the change in field magnitude after a reconnection may, in principle, be positive if only a small amount of flux is removed and the rate of addition of flux is high. This would be more likely to

occur for a substorm immersed in a storm. Nevertheless, for any substorm, one may observe that the "background field variation" (i.e., the field variation remaining after the extraction of the rapid reconnection perturbation) may be increasing or decreasing during the substorm.

Returning to the suggestion that the field is not perturbed throughout the whole tail when reconnection occurs, if the satellite is in such a position that it sees no reconnection effect, it will see the "background variation" defined above. This, of course, is true regardless of the model chosen to explain the non-uniform tail effect. Figure 6 shows quite a large variation of this type. One is tempted to suggest that during the period spanning the first three Pi2 onsets, the addition of field dominated the reduction due to implosive merging (not observable at the satellite), whereas during the fourth and possibly subsequent Pi2's reconnection dominated.

One final observation requires comment. When two or more Pi2's could be identified in association with a substorm no tail effect was ever observed with the first of such a sequence. Although this can be explained easily by the azimuthal sector model, the possibility still exists that the first discrete energy input in a substorm is initiated in the inner magnetosphere. Information from this disturbance then propagates into the magnetotail where it may trigger the first reconnection. This consideration may seem unwarranted on the basis of data presented. However, it is included as it was originally suggested by Rostoker (1968) as a possible explanation of the trigger bay/main bay phenomenon.

Further justification for keeping this possibility in mind can be found in the evidence presented in the above-mentioned paper, showing that the trigger bay is a small localized effect exhibiting a much smaller energy dissipation than the main bay. This, of course, does not define the mechanism but suggests that it may be different from the main bay and any subsequent energy inputs. Also, the observations of tail effects when only one Pi2 can be found do not invalidate this because the localized trigger bay is often difficult to find on normal magnetograms. Furthermore, because of its smaller energy dissipation, it may excite Pi2 micropulsations over a smaller area than the main bay. Therefore, it is possible that substorms for which only one Pi2 could be found had an earlier undetected trigger bay.

In conclusion, it is felt that rapid field line merging in a localized region of the magnetotail, providing the energy for the substorm, is a probable explanation of the results presented here. In particular the appearance of approximately 80% of the field in the negative Z direction on one occasion is difficult to explain by any other mechanism. Further, it seems that the energy is delivered into the upper atmosphere rapidly (within the 6 minute uncertainty inherent in this study). The increase of the perturbation field values outside Xsm ~ 21 Re suggests that the reconnection occurs beyond this value of Xsm at a position probably correlated with the intensity of magnetic activity. This observation is consistent with the work of Unti and Atkinson (1968) who showed that the neutral sheet and tail field are displaced earthwards with increasing tail flux (which we know is a function of the level of terrestrial magnetic activity).

CHAPTER 3

SOME RECENT OBSERVATIONS

Since this examination of substorm-associated tail effects was completed some interesting observations complementing this study have been published. Perhaps the most significant here are those of Fairfield and Ness (1970) obtained by a comparison of 2.5 minute averages of the AE index, and Imp 4 magnetic field data available with 20 second resolution.

Their statistical study indicates that in times of magnetic activity the magnetotail is more tail-like than at quiet times. This is shown by an average value of Bz of 1.8 when AE $\geq$ 20 γ compared with 2.8 for AE < 20 γ. Also, they confirmed the results of Behannon and Ness (1966) showing that the total field magnitude in the tail increases with AE.

On an individual substorm basis, they showed that typically, prior to the maximum values of AE, B would increase, but Bz would remain small and at a time "usually near the maximum value of AE", the field B would decrease with Bz simultaneously or shortly afterwards increasing. They were able to find only occasional examples of small negative Bz changes and from the examples shown in their publication these appeared to occur in no particular relation to the substorm. However, they found some cases where almost all the tail field was rotated into the positive Z direction.

Generally their results are in agreement with those presented earlier in this thesis. Although it may seem that some of their timing

disagrees with that shown in this study, such discrepancies are far more likely to result from study of the rather crude AE index substorm representation than the individual normal magnetograms supplemented with Pi2 micropulsations.

Russell et al. (1971) observed similar effects in the radial range 10 - 17 Re in data from OGO 5. On one inbound pass four substorm associated tail effects were observed near the expected position of the neutral sheet as computed from the Russell and Brody formula. On each of these, they observed a decrease in total field B and a positive change in Bz. However, they found that the increase in Bz in the last of these substorms occurred approximately fifteen minutes after the decrease in B commenced. This may indicate that the satellite initially observed a reduction in B in the form of background variation defined earlier due to flux removal from the tail, whereas the field magnitude decrease concurrent with the increasing Bz was intimately associated with reconnection. That is, in the former case, the satellite may have been well outside the volume of reconnecting lines, and in the latter case, inside. Alternatively, as the satellite was at a distance of approximately 7 Re for this last substorm, the initial reduction in B could result from the outward propagation of a rarefaction wave front behind which followed a reduction of magnetic and plasma pressure. The collapsing magnetic field following a reconnection triggered by this wave could be responsible, on reaching the satellite, for the appearance of the change in Bz.

Aubry and McPherron (1971) have attempted to correlate causes and manifestations of the magnetospheric substorm,and other changes in the

magnetosphere, from four locations. From interplanetary space they obtained magnetic field and plasma data of the solar wind from each of Explorers 33 and 35. Tail field data only were acquired from OGO 5 and Imp 4 as used by Fairfield and Ness (1970). Inner magnetosphere field data and ground magnetic field data were provided by the UCLA magnetometer on ATS 1 and various ground magnetograms, respectively. Their conclusions may be summarized as follows:

(1) The tail field slowly increases and slowly decreases with the appearance of southward and northward interplanetary field respectively in the absence of substorm activity.

(2) The tail field decreases slowly, in association with substorms.

(3) When the tail field increases it takes on a more tail-like configuration and the plasma sheet thins. When it decreases, from either of the above causes, it becomes more dipolar and the plasma sheet expands.

(4) Rapid decreases in tail field result only from the diamagnetic effect when the satellite is passed by the boundary of the thickening plasma sheet. Rapid increases occur only from the reverse of this. The former, therefore, may be in association with substorms or arrival of northward interplanetary field.

It should perhaps be mentioned that these conclusions were arrived at from consideration of their own data together with other known results. Also by rapid changes they refer to rates comparable with those observed in the study of this thesis and therefore their slow changes

refer to rates of change much less than these. Their intent was to demonstrate that the tail behaviour associated with substorms is similar to that due to other causes and much of the disagreement regarding, for example, time delays between earth and tail behaviour had resulted from this.

According to their interpretation, they would associate the rapid magnetic field changes in this study to plasma sheet boundary traversals. This was essentially an assumption (they had no particle data from Imp 4) supported by results of Lazarus et al. (1968) where rapid changes of field with corresponding changes of plasma pressure, such that the total magnetic plus plasma pressure was constant,were interpreted as plasma sheet boundary crossings. It is highly probable that magnetic field changes occurring while the total pressure remains constant are indeed plasma boundary traversals. Furthermore, some or all of those magnetic field changes observed by McPherron et al. may be of this nature. However, in the examples examined in this thesis, a clear field rotation is observed. As there is no reason to expect a significant change of field direction across the plasma boundary (indeed, there is every reason to expect the field to be approximately parallel to the boundary), it is submitted here that rapid changes in field magnitude <u>and</u> direction are <u>not</u> indicative of plasma boundary crossings, but <u>are</u> seen in association with substorms. It is further suggested that the slow substorm-associated decrease in field magnitude is observed by the satellite when it is not in the reconnection region. It then sees only the background field variation.

In summary, McPherron et al. have shown that changes in tail field

magnitude are related to the change of direction of the component of the interplanetary magnetic field perpendicular to the ecliptic plane. However, it is contended in this thesis that, on the basis of the currently available data, rapid changes in magnitude and direction of the tail magnetic field are solely substorm-associated phenomena.

Meng et al. (1971), using Imp 3 magnetic field data and energetic electron data (E > 50 kev), have examined substorm-associated events in the tail in three regions: (a) high enough above the neutral sheet so as to never become immersed in the plasma sheet; (b) the region which is in the plasma sheet when it is thick and not when it is thin; and, (c) the region which is always within the plasma sheet. (Although the plasma sheet electrons have only a small percentage of their population with energies in the E > 50 kev range, the existence of these energetic electrons is usually a reliable indication of the existence of the plasma sheet.) Their results indicate that typically, in the early phases of a substorm, the field magnitude outside the plasma sheet increases, while it decreases during the recovery phase. The plasma sheet thinning is observed downtail to at least a distance of 30 Re in the early phases and expands more rapidly sometime around the maximum development of the substorm. In region (b) the passing plasma boundary is accompanied by a large diamagnetic effect and "within the expanding plasma sheet, the northward component of B increases". It is believed that the authors are not implying that the increase in Bz appears discontinuously with the passage of the plasma sheet boundary. Certainly, the examples in their publication do not support this. Rather, their statement is interpreted to mean that over a period of

20 - 30 minutes while the plasma sheet is expanding, the value of Bz is increasing. Also, their examples show spikes in the B and Bz plots similar to those discussed earlier, although they do not relate them to any specific substorm feature.

Clearly the gross tail behaviour before, during, and after substorms seen in this study is in agreement with that of the previous publications discussed in this chapter. One can see, however, slight differences in the timing of the various correlations with ground based magnetometer data. This is no doubt due to the different criteria adopted to establish the substorm onset time, together with the use of a limited number of normal magnetograms which will tend to lead to disagreement between those not using the same set of magnetograms.

Finally, the contemporary understanding of the plasma sheet data at ~18 Re provided by the latest results from the Vela program are presented by Hones (1971). In essence, this involves a plasma sheet which thins gradually over a period of an hour or more prior to the onset of the expansive phase of a substorm. In this thinning, however, the density of the plasma is not increased and it is concluded that the plasma is driven earthwards creating a gradually deepening H trace on an auroral zone magnetogram. This corresponds to the growth phase discussed by McPherron (1970). After this, the onset of the substorm expansive phase occurs showing a very rapid decrease in the H trace in the auroral zone. This is accompanied by the onset of rapid thinning of the plasma sheet. Alternatively, the development or growth phase may not be observed and the onset of the expansive phase may appear without warning accompanied by the rapid thinning of the plasma sheet. Sometime after the onset of

the expansive phase the plasma sheet expands to a greater thickness than the presubstorm level.

In conclusion, the following is proposed as a plausible model of the magnetotail behaviour prior to and during substorms. At some time before the substorm, the total tail flux is increased due to removal of magnetic flux from the sunward side and delivery of this to the night side. The enhanced tail diameter produced creates a greater angle of flare at the boundary and a greater obstruction to the solar wind flow. This causes compression of the tail, which increases the magnetic field energy density thereby causing the plasma sheet to be compressed <u>gradually</u>. At some point in time determined by the energy resident in this magnetic field configuration, implosive reconnection is initiated in a series of bursts exhibiting a 15 - 20 minute periodicity. These occur in a succession of localized regions causing energy to be deposited in the upper atmosphere with the same periodicity. This causes the onset of the expansive phase and rapid plasma sheet thinning. Within the reconnection region violent field perturbations as shown in this thesis are observed. Outside this region, the field will continue to increase <u>gradually</u> if the field addition rate dominates the removal rate through reconnection. However, eventually, when the addition rate subsides, removal will dominate and the field will decrease <u>gradually</u>. Furthermore, removal of field in the distant tail (which then piles up at smaller radial distances in a more dipolar configuration) causes tail field lines which have <u>not</u> reconnected also to gradually adopt a more dipolar configuration throughout the tail. As this more dipolar field appears, the plasma sheet expands. Eventually, when enough energy has

been transported from the magnetotail to the inner magnetosphere, reconnection terminates.

It is felt that this model best explains the currently available data describing the character of the particles and fields in the magnetotail. The details of the model with regard to the proposed quasi-periodic implosive reconnection in spatially localized regions are viewed as a viable conceptual structure within which to interpret these data, though it may well be modified in the light of future observations.

BIBLIOGRAPHY

Akasofu, S.-I., *Polar and Magnetic Substorms*, D. Reidel, Dordrecht, Netherlands, 1968.

Alfvén, H., and C.-G. Fälthammer, *Cosmical Electrodynamics, fundamental principles*, p. 54, Clarendon Press, Oxford, 1963.

Anderson, K.A., Energetic electron fluxes in the tail of the geomagnetic field, *J. Geophys. Res.*, *70*, 4741, 1965.

Anderson, K.A., and N.F. Ness, Correlation of magnetic fields and energetic electrons on the IMP 1 satellite, *J. Geophys. Rev.*, *71*, 3705, 1966.

Atkinson, G., A theory of polar substorms, *J. Geophys. Res.*, *71*, 5157, 1966.

Aubry, M.P., C.T. Russell, and M.G. Kivelson, Inward motion of the magnetopause before a substorm, *J. Geophys. Res.*, *75*, 7018, 1970.

Aubry, M.P., and R.L. McPherron, Magnetotail in relation to the solar wind magnetic field and magnetospheric substorms, *J. Geophys. Res.*, *76*, 4381, 1971.

Axford, W.I., and C.O. Hines, A unifying theory of high latitude geophysical phenomena and geomagnetic storms, *Can. J. Phys.*, *39*, 1433, 1961.

Axford, W.I., The interaction between the solar wind and the earth's magnetosphere, *J. Geophys. Res.*, *67*, 3791, 1962.

Axford, W.I., Viscous interaction between the solar wind and the earth's magnetosphere, *Planet. Space Sci.*, *12*, 45, 1964.

Axford, W.I., H.E. Petscheck, and G.L. Siscoe, Tail of the magnetosphere, *J. Geophys. Res.*, *70*, 1231, 1965.

Axford, W.I., Magnetospheric convection, *Rev. Geophys. and Space Phys.*, *7*, 421, 1969.

Bame, S.J., J.R. Asbridge, H.E. Felthauser, R.A. Olson, and I.B. Strong, Electrons in the plasma sheet of the earth's magnetotail, *Phys. Rev. Lett.*, *16*, 138, 1966.

Beard, D.B., The interaction of the terrestrial magnetic field with the solar corpuscular radiation, *J. Geophys. Res.*, *65*, 3559, 1960.

Behannon, K.W., and N.F. Ness, Magnetic storms in the earth's magnetic tail, *J. Geophys. Res.*, *71*, 2327, 1966.

Biermann, L., Solar corpuscular radiation and the interplanetary gas, *Observatory*, *77*, 109, 1957.

Chapman, S., and V.C.A. Ferraro, A new theory of magnetic storms, *Terr. Magn. Atmos. Elec.*, *36*, 77, 1931.

Dessler, A.J., Length of the magnetospheric tail, *J. Geophys. Res.*, *69*, 3913, 1964.

Dessler, A.J., Magnetic merging in the magnetospheric tail, *J. Geophys. Res.*, *73*, 209, 1968.

Dungey, J.W., Interplanetary magnetic field and the auroral zones, *Phys. Rev. Lett.*, *6*, 47, 1961.

Fairfield, D.H., and L.J. Cahill, Transition region magnetic field and polar magnetic disturbances, *J. Geophys. Res.*, *71*, 155, 1966.

Fairfield, D.H., Polar magnetic disturbances and the interplanetary magnetic field, *Space Research*, *8*, edited by A.P. Mitra, L.G. Jacchia, and W.S. Newman, pp. 107-119, North Holland Publishing Co., Amsterdam, 1967.

Fairfield, D.H., and N.F. Ness, Magnetic field measurements with the IMP 2 satellite, *J. Geophys. Res.*, *72*, 2379, 1967.

Fairfield, D.H., and N.F. Ness, Configuration of the Geomagnetic tail during substorms, *J. Geophys. Res.*, *75*, 7032, 1970.

Freeman, J.W., The morphology of the electron distribution in the outer radiation zone and near the magnetospheric boundary as observed by Explorer 12, *J. Geophys. Res.*, *69*, 1691, 1964.

Heppner, J.P., N.F. Ness, C.S. Scearce, and T.L. Skillman, Explorer 10 magnetic field measurements, *J. Geophys. Res.*, *68*, 1, 1963.

Heppner, J.P., M. Sugiura, T.L. Skillman, B.G. Ledley, and M. Campbell, OGO-A magnetic field observations, *J. Geophys. Res.*, *72*, 5417, 1967.

Hill, T.W., and A.J. Dessler, Plasma sheet structure and the onset of magnetospheric substorms, *Planet. Space Sci.*, *19*, 1275, 1971.

Hones, E.W., Jr., J.R. Asbridge, S.J. Bame, and I.B. Strong, Outward flow of plasma in the magnetotail following geomagnetic bays, *J. Geophys. Res.*, *72*, 5879, 1967.

Hones, E.W., Jr., Substorm behaviour of plasma sheet particles, in *Earth's Magnetospheric Processes*, edited by B.H. McCormac, D. Reidel, Dordrecht, Netherlands, 1972.

Johnson, F.S., The gross character of the geomagnetic field in the solar wind, *J. Geophys. Res.*, *65*, 3049, 1960.

Kellogg,P.J., Flow of plasma around the earth, *J. Geophys. Res.*, *67*, 3805, 1962.

Kisabeth, J.L., and G. Rostoker, Development of the polar electrojet during polar magnetic substorms, *J. Geophys. Res.*, *76*, 6815, 1971.

Laird, M.J., Structure of the neutral sheet in the geomagnetic tail, *J. Geophys. Res.*, *74*, 133, 1969.

Lazarus, A.J., G.L. Siscoe, and N.F. Ness, Plasma and magnetic field observations during the magnetosphere passage of Pioneer 7, *J. Geophys. Res.*, *73*, 2399, 1968.

McPherron, R.L., Growth phase of magnetospheric substorms, *J. Geophys. Res.*, *75*, 5592, 1970.

Meng, C.-I., S.-I. Akasofu, E.W. Hones, Jr., and K. Kawasaki, Magnetospheric substorms in the distant magnetotail observed by IMP 3, *J. Geophys. Res.*, *76*, 7584, 1971.

Mihalov, J.D., D.S. Colburn, R.G. Currie, and C.P. Sonnet, Configuration and reconnection of the geomagnetic tail, *J. Geophys. Res.*, *73*, 943, 1968.

Murayama, T., Spatial distribution of energetic electrons in the geomagnetic tail, *J. Geophys. Res.*, *71*, 5547, 1966.

Ness, N.F., C.S. Scearce, and J.B. Seek, Initial results of the IMP 1 magnetic field experiment, *J. Geophys. Res.*, *69*, 3531, 1964.

Ness, N.F., The Earth's magnetic tail, *J. Geophys. Res.*, *70*, 2989, 1965.

Ness, N.F., The geomagnetic tail, *Rev. Geophys. and Space Phys.*, *7*, 97, 1969.

O'Brien, B.J., High latitude geophysical studies, *J. Geophys. Res.*, *69*, 13, 1964.

Parker, E.N., Interaction of the solar wind with the geomagnetic field, *Phys. Fluids*, *1*, 172, 1958.

Petscheck, H.E., Magnetic field annihilation, in *Proceedings of AAS-NASA Symposium on the Physics of Solar Flares*, NASA SP-50, edited by W.N. Hess, p. 425, 1964.

Piddington, J.H., Geomagnetic storm theory, *J. Geophys. Res.*, *65*, 93, 1960.

Piddington, J.H., A hydromagnetic theory of geomagnetic storms and auroras, *Planet. Space Sci.*, *9*, 947, 1962.

Rostoker, G., and C.-G. Fälthammer, Relationship between changes in the interplanetary magnetic field and variation in the magnetic field at the Earth's surface, *J. Geophys. Res.*, *72*, 5853, 1967.

Rostoker, G., Macrostructure of geomagnetic bays, *J. Geophys. Res.*, *73*, 4217, 1968.

Rostoker, G., and F.P. Camidge, The localized character of magnetotail magnetic fluctuations during polar magnetic substorms, *J. Geophys. Res.*, *76*, 6944, 1971.

Russell, C.T., and K.I. Brody, Some remarks on the position and shape of the neutral sheet, *J. Geophys. Res.*, *72*, 6104, 1967.

Russell, C.T., R.L. McPherron, and P.J. Coleman, Jr., Magnetic field variations in the near geomagnetic tail associated with weak substorm activity, *J. Geophys. Res.*, *76*, 1823, 1971.

Sonnet, C.P., D.L. Judge, A.R. Sims, and J.M. Kelso, A radial rocket survey of the distant geomagnetic field, *J. Geophys. Res.*, *65*, 55, 1960.

Sprieter, J.R., and B.P. Briggs, Theoretical determination of the form of the boundary of the solar corpuscular stream produced by interaction with the magnetic dipole field of the Earth, *J. Geophys. Res.*, *67*, 37, 1962.

Sweet, P.A., The production of high energy particles in solar flares, *Nuovo Cimento, Suppl.*, *8*, Ser. 10, 188, 1958.

Unti, T., and G. Atkinson, Two-dimensional Chapman-Ferraro problem with neutral sheet, *J. Geophys. Res.*, *73*, 7319, 1968.

Yeh, T., and W.I. Axford, On the reconnection of magnetic field lines in conducting fluids, *J. Plasma Phys.*, *4*, 207, 1970.